Power-Efficient Directional Wireless Communication on Small Form-Factor Mobile Devices

Ardalan Amiri Sani, Hasan Dumanli, Lin Zhong, and Ashutosh Sabharwal
Department of Electrical and Computer Engineering, Rice University
{ardalan, hasand, lzhong, ashu}@rice.edu

ABSTRACT

Wireless access is known to be power-hungry for mobile devices. A key reason is that devices radiate power in all directions and much of this power will not reach the destination. To address this waste, we present *BeamSwitch*, a multi-antenna system designed to realize directional communication efficiently. Unlike power-hungry and expensive beamforming, BeamSwitch requires only one transceiver. We provide an 802.11-compliant design and prototype of BeamSwitch. Our measurements show that with three passive directional antennas, BeamSwitch reduces the power consumption of a commercial 802.11 adapter by up to 20% and provide better quality under diverse propagation environments and extreme rotation.

Categories and Subject Descriptors

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

General Terms

Algorithm, Design, Experimentation, Measurement

Keywords

Passive directional antennas, mobile devices

1. INTRODUCTION

Current mobile devices employ omni-directional antennas and radiate power in all directions for wireless transmission. Such omni-directional radiation not only introduces interference between peers, but also leads to *directional waste of power*. This is particularly true when the devices are only communicating with a single party, e.g. in infrastructure networks such as cellular and WLAN.

The goal of this work is to solve these problems by focusing radiation in the right direction, a technique known as *directional transmission*. With directional transmission, a lower transmit power can potentially be employed to achieve the same received signal strength and therefore improve the energy efficiency of transmission. Directional communication has been extensively studied and deployed for base stations, access points, moving vehicles, and even sensor nodes. However, no one has studied or deployed directional communication to mobile devices such as smartphones that can not only move but can also rotate.

In this work, we present BeamSwitch, a system solution for directional communication on mobile devices. BeamSwitch achieves directionality by using passive directional antennas, or *directional antennas* for short, instead of phased-array antenna systems. BeamSwitch employs a special multi-antenna system that consists of multiple identical directional antennas, and a single regular omni antenna, all driven by *a single transceiver*. At a given time, only one antenna is used. BeamSwitch improves energy efficiency by reducing transmit power with the directional antennas. It is important to note that "antenna" is often used to refer to the whole RF system, including antennas and RF chains, e.g. phased-array antenna. In this work, we use "antenna" to refer to the actual antenna (radiating element) only.

By using directional antennas instead of phased-array antenna systems, BeamSwitch faces a new challenge in selecting the best antenna because mobile devices can not only *move*, but can also *rotate*. Rotation can introduce much faster direction changes than mobility can. BeamSwitch addresses the rotation of devices by leveraging the acknowledgement (ACK) mechanism and the channel reciprocity to assess the quality of an antenna *without probing*. Finally, BeamSwitch transmits only data frames and receives ACK frames through a directional antenna. For all other frames, it employs the omni antenna. Therefore, BeamSwitch is completely compliant with 802.11 protocols.

We make two contributions in this work:

- We present BeamSwitch, a design that realizes directional communication on mobile devices efficiently by carefully selecting from multiple antennas without any change to or cooperation from the deployed network infrastructure;
- We report a prototype implementation and demonstrate the feasibility of directional communication on mobile devices and its efficacy in saving power.

To the best of our knowledge, BeamSwitch is the first publicly reported realization of directional communication on a device that can rotate during usage like a smartphone. Our measurements show that by using three directional antennas with 5dBi maximum gain and with 3dB (or 50%) lower transmit power through the directional antennas, BeamSwitch can improve energy efficiency by over 20% for a commercial 802.11 adapter. BeamSwitch simultaneously improves communication quality by up to 20% in both stationary and low mobility (rotating at 90°/second) cases. It maintains similar efficiency improvement and a comparable communication quality even when continuously rotating at 360°/second. Note that the energy efficiency improvement will be much higher than 20% if BeamSwitch is applied to wireless transmission of longer ranges such as cellular networks for which transmit power dominates the total power consumption. A more complete evaluation of BeamSwitch is reported in [1].

The rest of the paper is organized as follows: Section 2 discusses related work. Section 3 offers the hardware design of BeamSwitch. Section 4 presents an 802.11-compliant design. Section 5 describes our prototype implementation and reports extensive measurements.

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Section 6 presents results from QualNet-based simulation that overcomes the limitations of our prototype. Section 7 concludes the paper.

2. BACKGROUND AND RELATED WORK

BeamSwitch is motivated by the commercial availability of passive directional antennas in small form factors that can be employed in smartphones and portable computers. For example, the patch antennas used in our prototype, which are designed for the 2.4 GHz frequency band, have an area of 3.2×3.2 cm^2 [2]. Using the 5 GHz frequency band allows the size of the antennas to be reduced even further. However, BeamSwitch is not restricted to patch antennas. For example, Multifunctional Reconfigurable Antennas (MRA), which use MEMS switches or microstrip parasitic array, enable multi beam patterns on a single antenna substrate [3, 4]. Sectorized antennas are also another alternative that provide multiple beams on a single substrate.[5] They are larger than MRAs and can only be deployed on bigger mobile devices, e.g. laptops. With these technologies, even small devices like smartphones could have up to six or eight beams in different directions. It is important to note that while many mobile devices actually employ two antennas [6-8], they do not use directional ones and are still considered omni-directional.

Despite the significant progress in directional communication, its use has been largely limited to base stations, access points, and vehicles, which have large footprints and no energy limitations, e.g. see [9, 10]. Therefore, directionality is almost always realized with expensive and power-hungry phase-array systems. The work that do employ directional antennas, e.g.[11], are intended for nodes that do not rotate. In contrast, BeamSwitch employs a single transceiver and passive directional antennas to bring directionality to mobile devices that can not only move but can also rotate.

3. BEAMSWITCH HARDWARE DESIGN

BeamSwitch employs multiple directional antennas and a single omni-directional antenna, all sharing a single transceiver through a software controllable switch. At any given moment, only one of the antennas is used. We include the conventional omni-directional antenna for standard compliance and for cases in which a proper antenna is difficult to identify. To realize the benefits in energy efficiency and interference of directional antennas, BeamSwitch employs a lower transmit power for a directional antenna. While the transmit power can be dynamically optimized, we limit our investigation to a fixed transmit power in this work due to space limitation. We denote the transmit power difference between the directional and the omni-directional antennas as P_{diff} (in dB).

If the directional antennas are identical and are uniformly placed on the mobile device, we call this setup a *symmetric design*. By uniformly, we mean that adjacent directional antennas are separated by the same solid angle. We note that it is almost impossible to have a perfectly symmetric design due to the form factor constraint. However, the symmetric design provides a reasonable approximation.

Although the radiation pattern is three-dimensional, we examine the two-dimensional pattern produced by a plane that goes through the origin of the three-dimensional antenna pattern. For clarity, we ignore the side lobes of the directional antenna. In our discussion, we refer to such a two-dimensional pattern of an antenna as a *beam*. Because of the symmetric design, the beams are uniformly distributed along a full circle centered around the origin. Figure 1 illustrates one beam (colored) and its neighbors. The beam has the highest antenna gain along its dominant direction, or G_{max}. In this work, we denote a configuration of the symmetric antenna system by a triplet (G_{max}, P_{diff}, number of beams). For example, the default configuration in our evaluation is (5,3,3).

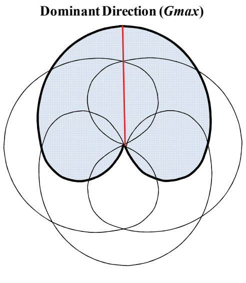

Figure 1: Planar antenna pattern of a symmetric complete design.

4. 802.11–BASED REALIZATION OF BEAMSWITCH

We next provide an implementation of BeamSwitch that is completely compliant with the 802.11 *infrastructure mode* based on the symmetric complete antenna system design. Our design does not require RTS/CTS. To ensure complete compliance with 802.11 and to minimize the deafness due to the use of directional antennas, BeamSwitch uses directional antennas only to transmit a data frame and to receive its ACK.

4.1 BeamSwitch Antenna Selection

The strategy of antenna selection without probing forms the foundation of our design. Our design consists of two key modules: *Antenna Assessment* module determines the threshold and whether the reward from the current antenna is over the threshold. If not, *Next Antenna* module suggests the next antenna for data transmission and therefore for Antenna Assessment. Note that there is no change to the 802.11 protocol and no need to transmit probing frames.

4.1.1 Antenna Assessment

The Antenna Assessment module leverages the acknowledgement mechanism and the channel reciprocity to assess *the received Signal-to-Noise Ratio (SNR) of an antenna as the reward*. Therefore, it employs the same antenna to receive the ACK as the one used for transmitting the corresponding data frame. The module estimates the received SNR of the transmitted data frame with the average *Receiver Signal Strength Indicator* (RSSI) of its ACK as obtained from the wireless transceiver [12]. The channel reciprocity assumption is reasonable because the interval between successive data and ACK packets is short, and because 802.11 usually has short range links and the same uplink and downlink frequency.

We have two heuristic methods to estimate the threshold in the antenna selection strategy. The more straightforward method is to use the average of the RSSIs of frames recently received on the omni-directional antenna. Such a threshold guarantees that a directional antenna will be no worse than the omni-directional antenna. Note that the 802.11-compliant BeamSwitch employs the omni-directional antenna for all frames except outgoing data and their ACKs. A more ambitious method is to estimate the threshold as the average of the RSSIs for the most recently received frames from both directional and omni-directional antennas, 50 frames in our implementation. Note that for the second method, the RSSIs of frames received on the omni antenna need to be adjusted before averaging to account for the transmission power difference between omni and directional antennas. The averaging compensates for the few possible RSSI reading outliers. Our implementation and reported evaluation is based on the second method.

Antenna Assessment module considers the current directional antenna as unfit if no ACK is received for the transmitted data frame, or the ACK RSSI is below the threshold. When the current antenna is unfit, BeamSwitch uses the Next Antenna module to identify the next antenna to send or resend the data frame, as described below. Because Antenna Assessment does not guarantee the optimality of the antenna that is over the threshold, we call the antenna the *right* antenna instead.

4.1.2 Next Antenna

The Next Antenna module suggests the antenna for the next outgoing data frame transmission or retransmission. Our design leverages the channel correlation between physically adjacent directional antennas and operates as a finite state machine. It first suggests the physical neighbors of the current directional antenna in a random order and then suggests the remaining directional antennas, again, in a random order. BeamSwitch updates its buffer with the RSSI value whenever receiving a frame. The state machine resets whenever a right antenna is identified.

The module will also suggest the omni antenna for safety when the retransmission of a data frame is reaching the MAC retransmission limit or when it has tried all directional antennas without finding a right one.

4.2 Analysis of BeamSwitch Performance

We make some important observations regarding the performance of BeamSwitch as dependent on the device rotation, traffic pattern, and antenna configuration. For simplicity, we assume there is no fading in the channel and only the Line of Sight path exists between a BeamSwitch node and its access point. Moreover, we focus on the rotation of a mobile device within one plane. That is, the node rotates around a fixed axis. Rotation round other axes can be analyzed in a similar way.

We first analyze the antenna gain for a single data frame that is transmitted T seconds after the previous frame, or more accurately the reception of its ACK. We assume that the BeamSwitch node is rotating at the speed of ω in its plane and that there are N beams in the same plane. Assuming a perfect threshold in Antenna Assessment, we find that the behavior of the antenna selection falls into three different cases, depending on how much the node rotates within T, or $T\cdot\omega$.

- When $T\cdot\omega \geq 4\pi/N$, the traffic is relatively sparse and the Antenna Selection will not find the right antennas in the first two tries and will try the rest of the antennas randomly.
- When $4\pi/N > T\cdot\omega > \pi/N$, the right antenna will be found in the first two tries.
- When $T\cdot\omega \leq \pi/N$, the traffic is relatively intense and BeamSwitch will use the right beam for most frames and can identify the right beam in first two tries for other frames.

First of all, we observe that *the expected antenna gain is dependent on $T\cdot\omega$. A smaller $T\cdot\omega$ implies higher average antenna gain and vice versa.* This means that a continuous traffic (smaller T) leads to better performance. Likewise, slower rotation, or smaller ω, leads to better performance.

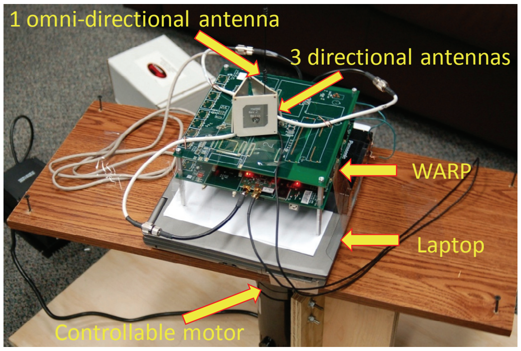

Figure 2: BeamSwitch prototype on the rotatable platform for experimentation

We further note that the choices of antenna configurations are indeed highly limited due to the following reasons.

- As $N\rightarrow\infty$, the traffic appears to be extremely sparse and Antenna Selection becomes less efficient.
- N must be large enough to ensure that the BeamSwitch antenna system can achieve performance comparable to the conventional omni design.
- N is constrained by the device form factor.

While it is impractical to derive a theoretically optimal antenna configuration for BeamSwitch as discussed above, in the next two sections, we seek to identify a *"good" antenna configuration* under diverse traffic and external settings using a prototype implementation and QualNet-based simulation. In Sections 5 and 6, we will experimentally demonstrate that a simple configuration, i.e. (5,3,3) , outperforms the conventional omni design under diverse traffic patterns.

5. EXPERIMENTAL EVALUATION

We have implemented the 802.11-compliant BeamSwitch on the Rice Wireless open-Access Research Platform (WARP) [13] and conducted a series of controlled experiments to evaluate its real-world performance (see Figure 2). The WARP platform supports 802.11-like communication at time-scales that are representative of commercial deployments.

5.1 Prototype

The WARP board supports two wireless transceivers, each with two antenna ports that can be selected in software. Therefore, we are limited to four antennas, three directional and one omni, in our prototype. Moreover, instead of using an antenna switch to select from multiple antennas, we have to employ both transceiver switches to select from the four antennas. However, at any given time, only one transceiver is active and the idle one is powered off. The prototype uses one Telex 2406 omni-directional antenna [14] and three directional antennas with G_{max}= 5dBi [2]. We lower the transmit power by 3dB or 50% for directional antennas. Unless otherwise specified, the default antenna configuration is (5,3,3). We implement BeamSwitch by modifying existing PHY and MAC code base. The implementation uses 2.4 GHz and employs QPSK with 12Mbps PHY layer data rate.

5.2 Experimental Setup

Our experiments involve two boards: one with BeamSwitch implemented, acting as the wireless interface for a laptop computer; the second without BeamSwitch, acting as the wireless interface for another laptop serving as the access point. The boards are placed at the same height and 15 meters from each other. We choose 15 meters because communication indoors is no longer reliable due to the range limitation of the WARP platform.

We test our prototype with high-definition video streaming using VLC media player (Video), transferring a large file (FTP), both from the BeamSwitch end, and also Remote Desktop (R. Desk) with the BeamSwitch end as the remote end. Each measurement lasts for five minutes for all benchmarks.

To stress BeamSwitch with controllable mobility, we build a motor-driven rotating platform to hold the battery-powered BeamSwitch end. The motor can rotate up to 360°/second. Figure 2 shows the BeamSwitch prototype on the rotatable platform. Note that random changes in the rotation direction will not make a difference, because the Next Antenna module is inherently random in its search. Therefore we report data for various rotating speeds only.

We evaluated the prototype both outdoors and indoors. *Outdoors* is an open space on a university campus. It is close to a Line of Sight channel where the multi-path effect is highly limited. *Indoors* is a cross-office scenario with no Line of Sight. It is close to a Rayleigh channel where the multi-path effect dominates. *Indoors2* is inside a hallway of a building with the Line of Sight path between the transmitter and receiver and with people walking around them. This environment is close to a Ricean channel.

5.3 Evaluation Metrics

We evaluate BeamSwitch on its energy saving and impact on communication quality. We evaluate the energy efficiency with Energy Per Bit (EPB), calculated as the total energy consumed by the Wireless Network Interface Card (WNIC) on the BeamSwitch end divided by the number of data bits successfully transmitted. The total energy includes energy consumption during receiving to account for the possible extra receiving energy introduced by BeamSwitch. Antenna switch uses a negligible amount of energy; hence it is not included in the total power. We report reduction in the energy per bit of the BeamSwitch end as compared to that of a conventional omni-directional end under the same experimental settings. Because WARP boards are not optimized for power, we employ a power model constructed with our measurements of a Cisco Aironet Wireless Cardbus 802.11 adapter [15] and calculate the total energy consumption of the whole card using traces collected from the BeamSwitch prototype.

We evaluate the impact of BeamSwitch on communication quality with throughput and data Retransmission Rate (RR). We calculate the throughput by dividing the number of correctly transceived data bits by the time of the experiment. We calculate the retransmission rate as the percentage of retransmitted data frames out of all transmitted data frames from the BeamSwitch end.

5.4 Measurement Results

Efficiency and Performance Gains: Our measurements, presented in Figures 3-5, clearly show that significant gains are possible with BeamSwitch. BeamSwitch can improve both energy efficiency and communication quality even under 90°/second rotation for all three benchmarks in all environments. In particular, we observe up to 20% throughput improvement for FTP, and up to 20% energy per bit reduction for Video. BeamSwitch only slightly degrades the communication quality even when continuously rotating at 360°/second. We observe no frame delay beyond 10ms. For Video and Remote Desktop, there is no human-perceptible difference in the media quality or response time. For FTP, throughput degrades by at most about 10% when continuously rotating at 360°/second.

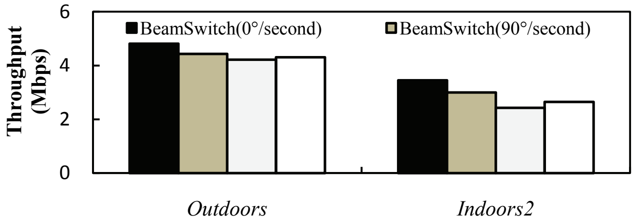

Figure 3: FTP throughput. BeamSwitch improves the throughput for rotation up to 90°/second and degrades throughput slightly when rotating at 360°/second

Rotation: Mobile devices are very unlikely to continuously rotate at 360°/second under realistic settings. Our own personal experience is that the rotation is more likely to be sporadic, and continuous direction changes are only introduced by linear mobility, and are therefore slow. Henceforth, we expect that gains of BeamSwitch in performance and energy efficiency will increase under realistic device usage. Moreover, as our experiments show, the communication quality impact due to sporadic rapid rotational mobility is very small and not perceptible to the end user.

Traffic Pattern: BeamSwitch has a relatively higher impact on the communication quality for Remote Desktop (R. Desk) than for Video and FTP. This is consistent with our analysis in Section 4.2, as Remote Desktop generates a bursty traffic. BeamSwitch achieves higher energy per bit reduction for Video than for FTP because Video is ~100% data transmission, but FTP requires a small percentage of data reception for FTP acknowledgements.

Effectiveness of Antenna Selection: Figure 4 shows that BeamSwitch identifies the right beam in the first two tries over 80% of the times even when the BeamSwitch end rotates at 360°/second under *Indoors2*. This corroborates our heuristic Next Antenna module described in Section 4 that suggests the two neighbors first. We also emulate the assistance of motion estimation (ME), in which BeamSwitch knows the direction of rotation. We measure FTP and Remote Desktop under *Indoors2* and *Outdoors* at 360°/second, as summarized in Figure 5. Our measurements show that the Motion Estimation (BeamSwitch-ME) reduces retransmission rates very close to or even lower than those for the conventional antenna counterpart. This highlights the potential for improving BeamSwitch with low-power sensors such as an accelerometer.

6. SIMULATION-BASED EVALUATION

We complement our prototype-based evaluation with simulations based on QualNet, a state-of-the-art wireless network simulator [16]. The simulations enable us to address the limitations of our prototypes in two aspects, namely, antenna system configurations with more beams, and more complicated mobility. Using the simulations, we are able to validate the heuristics used in the Antenna Selection design as well as the performance model described in Section 4.

6.1 BeamSwitch in QualNet

We have modified the PHY and MAC layers of the QualNet simulation tool to simulate BeamSwitch. We have implemented the radiation model for the same 5dBi directional antenna used in our prototype [2]. QualNet provides an energy model for the WNIC derived from the WaveLAN specification [16]. Unless otherwise specified, all simulations are conducted with the BeamSwitch de-

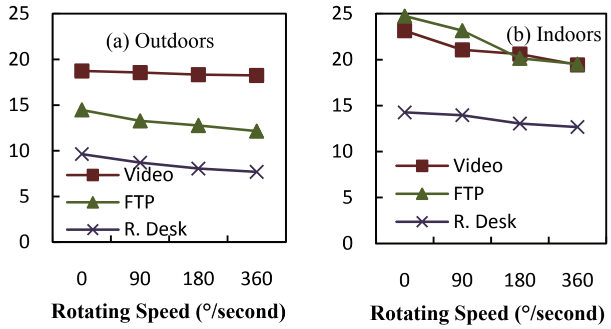

Figure 4: Energy per bit (EPB) reduction for BeamSwitch (%)

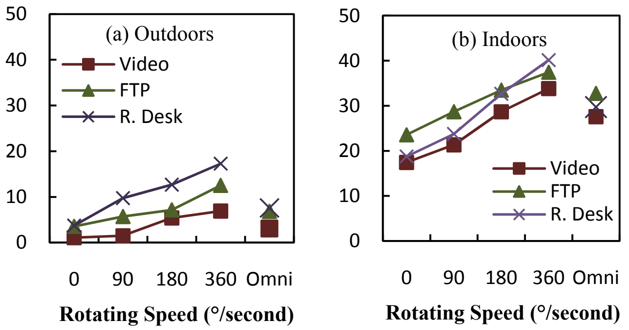

Figure 5: Retransmission rate (RR) for BeamSwitch and conventional omni designs (%)

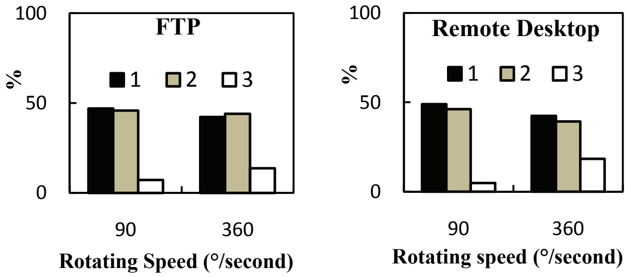

Figure 6: Histogram of the number of trials before the right beam is identified in *Indoors2.* BeamSwitch identifies the right beam within the first two trials over 80% of the times

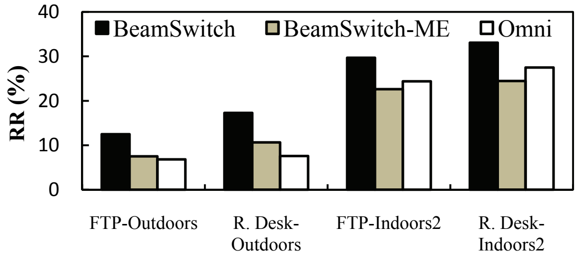

Figure 7: Motion Estimation (BeamSwitch-ME) reduces retransmission rates (RR) to very close to the conventional omni-directional design even at 360°/second

vice placed 150 meters from the access point. All simulations are based on the 11Mbps PHY layer, and RTS/CTS is not used. The default antenna configuration is identical to that in our prototype, i.e. (5,3,3). QualNet allows us to move and rotate each node. We employ the built-in Line of Sight channel from QualNet. This is an extremely challenging channel for BeamSwitch because it magnifies the hidden node problem and the cost of antenna assessment.

6.2 Number of Beams

We first examine the impact of the number of directional antennas (5dBi antennas), or beams, which was not possible with the prototype. Figure 8 presents the retransmission rate vs. the number of beams when the Beamswitch node is rotating at 360°/s for Poisson traffic of various mean packet interval ($1/\lambda$) and VoIP traffic provided by Qualnet. Note that retransmission rate can be considered as a monotonically decreasing function of the expected antenna gain. Figure 8 (left) shows that there is an optimal number of beams for a given traffic, and that the optimal number increases as traffic becomes intense.

Figure 8 (right) for VoIP highlights the impact of a more complicated traffic pattern. It shows that the retransmission rate for VoIP traffic increases first, decreases then, and finally increases again as the number of beams increases. This can be explained by the two inherent patterns in the VoIP traffic. The first pattern is its burstiness, which can be viewed as a Poisson process with a very small λ. The second pattern is inside a burst that can be viewed as a Poisson traffic with a very large λ. The final trend of plots is a result of the interplay of both patterns.

6.3 Design of Next Antenna

We first provide simulation results to support our heuristic design of the Next Antenna module described in Section 4.1. Recall that the module suggests which antenna to use when the Antenna Assessment determines the current one to be unfit. Our prototype has only three directional antennas; therefore, the Next Antenna module is simplified, as it only tries the other two antennas in a random order. We next employ a (5,3,6) configuration that has 6 directional antennas to examine the Next Antenna module design. Recall that the BeamSwitch heuristic method is to try the two neighbors in a random order first and then try the rest of the antennas again in a random order. We compare this method with several alternatives described below. *Random* tries all the antennas in a random order. *Sequential-Correct* always tries the next adjacent antenna along the correct direction. This method is possible if BeamSwitch knows the direction of the rotation of the device. *Sequential-Incorrect* always tries the next adjacent antenna along the wrong direction. Finally, *BeamSwitch-ME* first tries the adjacent antenna along the correct direction and then tries the rest of the antennas in a random order. Figure 9 summarizes the results of retransmission rates under different rotating speeds. It shows that *Random* is inferior because it does not leverage the correlation between neighboring antennas. Sequential is very good if it knows the direction of rotation, i.e. *Sequential-Correct*, but is the worst method if it does not know the direction of rotation, i.e. *Sequential-Incorrect.* BeamSwitch heuristic method achieves the best result when the rotation direction is unknown. Moreover, motion estimation can improve BeamSwitch, i.e. *BeamSwitch-ME*, to the point that it is even better than *Sequential-Correct*.

6.4 Random Mobility

In Section 5, we mentioned that the randomness in the antenna selection makes the evaluation with random direction changes unnecessary. We have simulated BeamSwitch with random direction changes. Our results confirm that random mobility does not introduce any noticeable difference in evaluation metrics values.

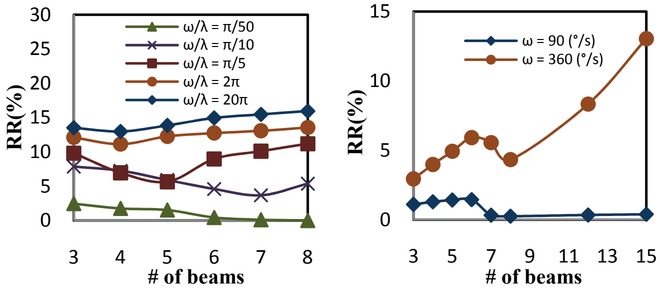

Figure 8: Retransmission Rate vs. Number of beams: (Left) Poisson traffic (Right) VoIP

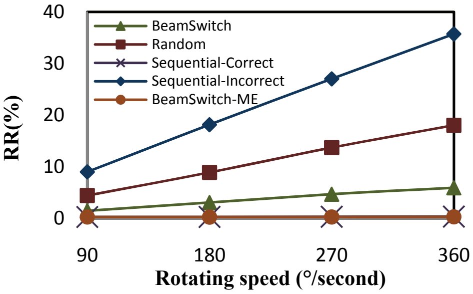

Figure 9: Retransmission Rate for different Next Antenna methods for (6-3-6) configuration with VoIP

As we recall from Section 4, BeamSwitch updates the threshold for Antenna Assessment even with RSSIs from the omni antenna. This helps distinguish between RSSI changes introduced by direction change and those by the mobile device moving away from its AP. To show its effectiveness, we simulate a BeamSwitch node moving away from the AP at two meters per second from 20 to 80 meters with VoIP traffic between them. Our results show that the retransmissions rate is below 1% and over 5% before and after the threshold updating with the omni antenna is disabled, respectively.

7. CONCLUSIONS

We present BeamSwitch, a first-of-its-kind system solution to realize energy-efficient directional communication on mobile systems. We report a prototype of the 802.11-compliant BeamSwitch and an extensive evaluation based on both the prototype measurements and simulations.

Our evaluation clearly demonstrates the effectiveness of BeamSwitch in improving energy efficiency (over 20%) of a commercial 802.11 WNIC with better or close communication quality compared to conventional systems based on the omni directional antenna. BeamSwitch achieves this improvement under extreme mobility (rotating at 360°/second) and under various radio propagation environments. It is important to note that BeamSwitch will be even more effective in terms of energy saving in cellular networks where long range communication results in high percentage of transmit power.

Also, our work reveals the potential improvement to BeamSwitch from sensor-based motion estimation. Our evaluation also shows that a simple antenna configuration with only three beams and therefore low form factor requirement can achieve robust and consistent improvement over conventional omni antenna based systems. Such a design may be readily deployed to mobile systems like smartphones and netbooks.

8. ACKNOWLEDGEMENTS

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