MobiCom 2010 Poster: BeamAdapt: Energy Efficient Beamsteering on Mobile Devices

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All current mobile devices are omni directional in transmission, which not only limits device energy efficiency but also poses a significant challenge toward network capacity through inter-link interference. In this work, we make mobile devices directional with beamsteering. By allowing a dynamic number of antennas in beamsteering, we reveal an important tradeoff between device energy efficiency and network capacity. We then provide a distributed algorithm called BeamAdapt that allows each mobile device in the network to closely approach the optimal tradeoff, with minimum aggregated device power to achieve certain network capacity. We also offer a cellular system realization of BeamAdapt as well as a Qualnet-based evaluation. The results show the effectiveness of BeamAdapt in device power reduction without sacrificing network throughput.

I. Introduction

All existing wireless standards assume that their mobile clients are omni directional in transmission. Such omni directionality yields a critical challenge not only to network capacity but also to client efficiency as the number of mobile devices dramatically increases. In this work, we study a client-based approach towards addressing the above challenge: *using beamsteering on mobile devices for directional transmission*. By focusing the transmit power towards the intended direction, beamsteering can not only reduce the transmit power waste but also reduce the interference to peer links. While directional transmission can be enabled by passive directional antennas e.g. [1, 2], the performance is largely constrained by both the small number of antennas and the difficulty of antenna selection. On the contrary, beamsteering as an alternative realization can form a beam towards arbitrary direction, and automatically find the best direction by channel state information (CSI) estimation.

By allowing beamsteering with a dynamic number of antennas, we reveal an important tradeoff between device efficiency and network capacity. Different number of antennas with their associated RF chains yields different power consumption to the transceiver, and meanwhile exhibits diverse beam shapes, which indicate various interference condition and network capacity. To approach the optimal tradeoff that achieves certain network capacity with minimum aggregated device power, we propose a distributed algorithm, called *BeamAdapt*, with which each mobile client iteratively adjusts its number of antennas and transmit power without coordination. The algorithm is guaranteed to converge to a near optimal performance. We further offer a system design of BeamAdapt in the context of modern cellular networks. We evaluate the cellular system realization of BeamAdapt with Qualnet-based simulation of a large-scale network. The results show that on average BeamAdapt can reduce client power consumption by 40% and 55% with two and four antennas, respectively, while maintaining the same network throughput. More concrete simulation results are reported in [3].

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II. BeamAdapt: Distributed Mobile Beamsteering

In this section we offer the theoretical framework as well as the cellular system design of BeamAdapt.

II.A. Tradeoff Analysis

We first highlight the tradeoff made by beamsteering on mobile devices. Firstly, compared to an omni directional antenna, beamsteering increases circuit power by multiple RF chains, but it uses a reduced transmit power to deliver the same received signal strength (RSS). Therefore, given the required RSS, an optimum number of antennas that minimizes device power consumption can be identified.

More importantly, beamsteering can significantly reduce network interference by focusing the radiation power to the intended receiver. Consequently, each mobile client in the network faces a balance between its energy efficiency and interference caused to peers.

The optimal number of antennas in terms of device efficiency is usually not the one yielding minimum interference to the network. The research question we seek to answer is: how could mobile clients of a large network independently identify their optimal number of antennas in beamsteering that *collectively minimize aggregated client power consumption to achieve certain network capacity*?

II.B. Theoretical Formulation and Solution

We formulate the question proposed above as an optimization problem:

Minimize

$$P_{Network} = \sum_{i=1}^{M}\left((1+\alpha)P_{TX,i} + N_i P_{Circuit} + P_{Shared}\right),$$

s.t.

$$SINR_i \geq \rho_i, 1 \leq N_i \leq N_{i,max}, \forall 1 \leq i \leq M,$$

The notation is explained as follows: $P_{Network}$ denotes the aggregated client power consumption. The client power consumption includes three components: the power consumption of all the power amplifiers in beamsteering, $(1+\alpha)P_{TX,i}$; the circuit power of each active RF chain, $N_i P_{Circuit}$; the power of circuitry shared by all RF chains, P_{Shared}. $P_{TX,i}$ is the transmit power and N_i is the number of antennas in beamsteering no larger than $N_{i,max}$. $SINR_i$ and ρ_i represent the actual and required SINR respectively.

We highlight that the problem is non-convex and involves integer constraints so that solving it is non-trivial. An exhaustive search algorithm can yield complexity as high as $O\left(\prod_{i=1}^{M}(N_{i,max})\right)$. To tackle this problem, we introduce an iterative algorithm, BeamAdapt, with near-optimal performance and much lower complexity.

We start with rewriting the problem as multiple sub-problems, i.e., the ith problem ($i = 1,2,\cdots M$) is

$$min_{P_{TX,i},N_i}\left((1+\alpha)P_{TX,i} + N_i P_{Circuit} + P_{Shared}\right),$$

$$s.t.\ SINR_i \geq \rho_i, 1 \leq N_i \leq N_{i,max}.$$

The optimal pair $(P_{TX,i}, N_i)$ is adjusted iteratively. That is, we assume the transmit power and the number of antennas in beamsteering are $P_{TX}^{(k-1)}$and $N^{(k-1)}$ for the (k-1)th iteration, and the actual link SINR is $SINR^{(k-1)}$, then for the kth iteration, $P_{TX}^{(k)}$ and $N^{(k)}$ can be obtained by solving the following optimization problem:

Minimize

$$(1+\alpha)P_{TX}^{(k)} + N^{(k)}P_{Circuit} + P_{Shared}$$

s.t.

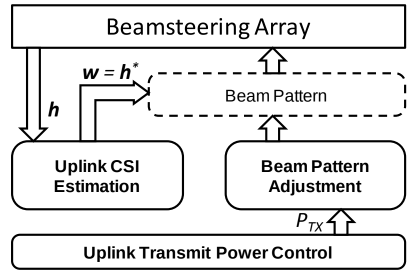

Figure 1. BeamAdapt implementation in the PHY layer of the UE

$$\frac{P_{TX}^{(k)}N^{(k)}}{P_{TX}^{(k-1)}N^{(k-1)}} = \frac{\rho}{SINR^{(k-1)}}, N^{(k)} \geq N^{(k-1)}.$$

We set $N^{(0)} = 1$, while $P_{TX}^{(0)}$ can be arbitrary. The iteration stops when $\left|SINR^{(k)} - \rho\right| \leq \varepsilon$, where ε can be set according to the requirement of accuracy, and then $(P_{TX}^{(k)}, N^{(k)})$ is accepted as the optimal beam pattern. Noticeably, BeamAdapt achieves a complexity of $O\left(\max(N_{i,max})\right)$. In addition, we can show the guaranteed convergence and near optimality of BeamAdapt [3].

II.C. Cellular System Realization

BeamAdapt can be readily implemented on the mobile client of a cellular system, as shown in Figure 1. The main components include *Uplink CSI Estimation* and *Beam Pattern Adjustment*. Uplink CSI estimation is used to calculate the beamsteering weight vector. We adopt explicit CSI estimation in BeamAdapt. That is, the client concatenates a short field made up of several training symbols to the data field in each uplink frame. Seeing the training symbols, the base station can estimate uplink CSI and send it back to the client during downlink control signaling and the client forms a beam as appropriate. Beam pattern adjustment resides on top of uplink transmit power control. Each time when the client receives the power control command from its base station, i.e., when the required transmit power is updated, beam pattern adjustment finds the most efficient beam pattern by identifying the optimal transmit power P_{TX} and number of antennas N.

III. Evaluation

We evaluate BeamAdapt with a focus on its benefit in client efficiency. We employ Qualnet [4] to emulate a close-to-reality cellular network where seven base stations and thirty mobile clients are put in a 4km × 4km area. The base stations have fixed locations, with the distance between adjacent ones set to 1.5km. The clients are allowed to have mobility with random speed between zero and seventy miles per hour. We add a FTP application to the client to mimic continuous uplink data transmission.

Figure 2 shows the average power consumption of the mobile client for transmitting as well as the network throughput under BeamAdapt, beamsteering and omni directional transmission. We denote BeamAdapt with two, four and eight antennas as BA2, BA4 and BA8. Similarly, beamsteering with two, four and eight antennas are referred as BS2, BS4, and BS8. Note that BS*x* always uses *x* active antennas while BA*x* can choose the number of antennas from 1 to *x*. We can clearly observe the power savings by BeamAdapt: BA2, BA4 and BA8 saves 43%, 54% and 56% client power respectively compared to omni directional transmission. Meanwhile, it can be seen that BeamAdapt achieves approximately the same network throughput as beamsteering and omni-directional transmission does.

IV. Ongoing and Future Work

We are currently expanding both theoretical and experimental aspects of BeamAdapt.

IV.A. Theoretical Investigation

An underlying assumption within the formulation in Section II is that the beamsteering vector has been chosen to maximize the gain of the intended receiver. While it is optimal from a single link perspective, steering the beam towards the intended receiver can be network-wise sub-optimal. This is due to the considerable width of the beam especially with a small number of antennas. When the unintended receiver is close to the intended one in terms of direction, beamsteering is very likely to cause more interference than omni directional transmission. Nonetheless, slightly rotating the beam may sacrifice the directional gain of the intended receiver but greatly reduce the interference to others, which may eventually offer higher network capacity. Therefore, we will incorporate this degree of freedom into BeamAdapt by allowing the beamsteering vector to be arbitrary.

IV.B. Experimental Evaluation

Previous system work on beamsteering all assume a pre-defined beam pattern, e.g. [5, 6]. Consequently, they either use a training based beam selection or exhaustively search among all possible beam patterns. On the contrary, BeamAdapt adopts real-time beamsteering, which requires a high-resolution tracking of the CSI. This is very challenging in practice considering that a mobile client can not only move but can also rotate. Due to its flexibility and programmability, we employ WARP [7] as our experimental platform. Although it is not compatible with cellular protocols, we note that the fundamental

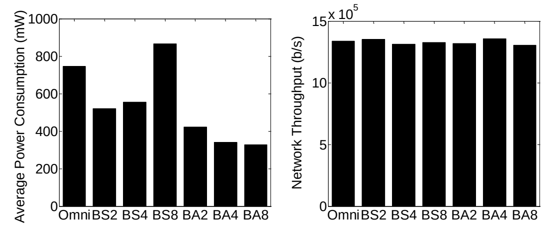

Figure 2. Client power consumption and network throughput of BeamAdapt, beamsteering and omni directional transmission

mechanism of BeamAdapt, i.e. beamsteering with dynamic number of antennas, is independent of the operating protocol.

We have performed experiments regarding the impact of device mobility on the beamsteering gain for an end-to-end link. The results showed that even under a very high rotation speed of the device, e.g. 180˚/s, the beamsteering gain remains high if the CSI estimation frequency is every 10ms. Currently we are extending the experiment to a network with multiple links. We will use a beamsteering transmitter as the mobile client and multiple omni receivers as different base stations. In addition, we will implement the full functionality of BeamAdapt on WARP including the adaptation of the number of antennas and transmit power.

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