Channel Capacity Optimization for an Integrated Wi-Fi and Free-space Optic Communication System (WiFiFO)

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ABSTRACT

Recent advances in free-space optical technology promise a complementary approach to increasing wireless capacity with minimal changes to the existing wireless technologies. This paper puts forth the hypothesis that it is possible to simultaneously achieve high capacity and high mobility by developing a communication system called WiFiFO (WiFi Free space Optic) that seamlessly integrates the recent free-space optics technologies and the current WiFi technologies. We briefly describe the WiFIFO architecture then discuss the main contribution of this paper that is optimizing the capacity of the proposed WiFiFO system. Specifically, we consider the problem of power allocation for multiple FSO and WiFi transmitters in order to achieve maximum system capacity for given budget power. A mathematical model of the combined capacity of FSO and WiFi channel is derived. We show that the power allocation problem for WiFiFO can be approximated well as a convex optimization problem. To that end, an algorithm based on gradient decent method is developed. Simulation results indicate that the proposed algorithm, together with system architecture can provide an order-of-magnitude increase in capacity over the existing WiFi systems.

Categories and Subject Descriptors

C.2.1 [**Computer communication networks**]: Network architecture and design; C.2.5 [**Computer communication networks**]: Local and wide-area networks

Keywords

Free space optics; WiFi; Hybrid network; Capacity; Power allocation; Optimization

1. INTRODUCTION

Recent advances in free-space optical technology promise a complementary approach to increasing wireless capacity with minimal changes to the existing wireless technologies [1], [2].

Specifically, the solid state lighting technology such as Lighting Emission Diode (LEDs) is now sufficiently mature that it is possible to transmit data at high bit rates reliably. Importantly, the free-space optical technology would not interfere with the typical RF transmissions such as WiFi devices, thus will enhance wireless capacity. However, such high data rates are currently achievable only with spot-light and short distance transmissions. This drawback severely limits the mobility of free-space optic wireless devices. This paper puts forth the hypothesis that it is possible to simultaneously achieve high capacity and high mobility by developing a communication system called WiFiFO (WiFi Free space Optic) that seamlessly integrates the recent free-space optics technologies and the current WiFi technologies. We briefly describe the proposed WiFiFO system in order to provide sufficient context for the main contribution of the paper. Specifically, this paper is focused on the problem of determining the power allocation for multiple FSO and WiFi transmitters in such a way to maximize the system capacity subject to a given power budget.

We note that there have been several studies on FSO/RF hybrid systems. The majority of these studies, however are in the context of outdoor point-to-point FSO transmission, using a powerful modulated laser beam[3], [4]. For more literature on this topic, please see [5], [6].

2. OVERVIEW OF WIFIFO

Consider the mostly widely deployed WiFi system 802.11g with a theoretically maximum rate of 54 Mbps. Typical WiFi networks operate at only a fraction of the maximum capacity, e.g., 5-15 Mbps. This rate reduction is due to a number of factors including the MAC protocol overhead and the distances between wireless devices and the access point (AP). Similarly, the 802.11n standard with its MIMO (Multiple Input Multiple Output) technology can increase the theoretical capacity, but the actual capacity is significantly less, e.g., less than 100 Mbps, depending on the operating scenarios. A simple calculation shows that such limited wireless capacities fail to provide adequate bandwidth for many scenarios.

The proposed WiFiFO system aims to overcome the WiFi overload problem by enhancing wireless capacity using complement FSO technology which does not interfere with the WiFi transmission bands. When leveraged with the existing high-speed (Gigabit) Ethernet infrastructure, the pro-

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posed WiFiFO based just on the current FSO technology can provide a typical bandwidth of *50 Mbps per user* via *local transmissions*; Fig. 1 illustrates a typical setting for the proposed WiFiFO system. In this setting, the focus will be on the common downlink scenario where most of users will download contents from the Internet via an AP. Although users can move around, they are often stationary, e.g., sitting on terminal benches at airports or lounges in hotel lobbies. As such, a network of FSO transmitters LEDs, with the high-speed Ethernet infrastructure can be deployed directly above the appropriate spots to provide local high-rate FSO transmissions most of the time, in addition to the WiFi transmission. For the height of a typical room, the beam cone of a LED covers a small area, approximately less than one meter square directly below. Thus a laptop or a PC located in this area equipped with a silicon photodiode (PDs), i.e., the receivers, can receive data via local FSO transmissions with rates depending on the distances to the center of the projected cone. To enable wireless devices to seamlessly and optimally operate simultaneously in both FSO and WiFi channels, the WiFiFO architecture implements a number of salient features. First, the WiFiFO implements a logical layer that monitors and manages the connections based on the FSO and WiFi channel conditions. That said, the movement patterns and locations of a user relative to the transmission-cone of the LEDs dynamically determine the amount of additional FSO bandwidth for the user. As such, the feedback on both WiFi and FSO are critical to allow optimal rate allocation between the two channels . However, at the present, the feedback capability via the FSO channel is not yet practical due to the cost/power of modulating an LED in a user device. To solve this problem, the WiFiFO system uses the WiFi channel to continuously monitor and provide feedback from a receiver to the AP when the devices move around from one FSO transmission cone to others.

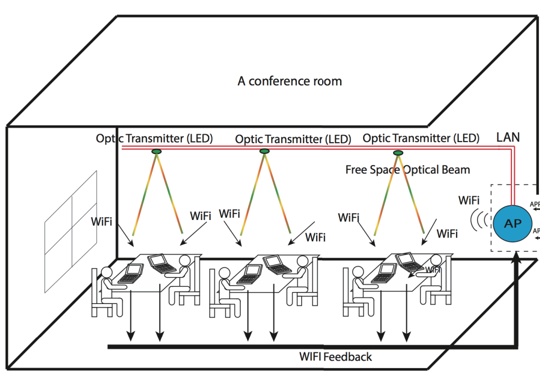

Figure 1: A realistic scenario for WiFiFO systems

The aim of the WiFiFO system is to overcome a number of practical challenges in today's WiFi networks, specifically the WiFi overload problem. The WiFiFO system will provide the high mobility of the current WiFi technology at the same time significantly increase the overall wireless capacity through local Free Space Optic (FSO) transmissions. While providing additional bandwidth through Free Space Optic technology is an obvious solution, there are several key challenges, including the design of a software and hardware architecture that optimally integrates the FSO and WiFi technologies, developing optimal packet transmission policies and coding techniques based on heterogenous requirements from various applications and devices operating simultaneously on both FSO and WiFi channels, and the implementation of modulation techniques that dynamically adjust the transmission rates based on the varying channel characteristics of FSO and WiFi channels as well as application and device requirements. This paper will focus on a specific challenge of the proposed WiFiFO system. Specifically, *the paper will focus on how to allocate power for FSO transmitters and WiFi in order to maximize the capacity. We present this problem as convex optimization and describe an projected gradient algorithm for finding the optimal power allocation scheme.*

3. CHANNEL MODELS

To describe the mathematical models for FSO and WiFi channels, we use the notations shown in Table 1.

B_{FSO}, B_{RF}	Optical and WiFi channel bandwidths, resp.
p_{Ot}, p_{Or}	Transmitted and received optical power, resp.
$p_{Ot,max}$	Max. optical transmission power
p_{RFt}, p_{RFr}	Transmitted and received WiFi power, resp.
$p_{RFt,max}$	Maximum WiFi transmission power
p_{total}	Total transmission power for WiFi and FSO
p_{noise}	Noise power of a WiFi receiver
r	Distance from optical receiver to cone center
d	Distance between WiFi receiver and AP
N	Total number of receiver
P	Theoretical FSO channel bit error rate

Table 1: Notations

3.1 FSO Channel Model

The light comes out of an LED is assumed to be Gaussian beam. The intensity (power per unit area) $I(r,z)$ received at the receiver can be computed as [7]:

$$I(r,z) = I_0 \left(\frac{w_0}{w(z)}\right)^2 \exp\left(\frac{-2r^2}{w^2(z)}\right), \tag{1}$$

where z is the distance to the transmitter, r is the distance to the center axis. $w(z)$ is the beam width that the intensity drop to $1/e^2$ of its center axis value. $w(z)$ is calculated by assuming the beam is a right circular cone with aperture $2\theta = 30°$. Given the transmission power p_{Ot}, the intensity at distance z and radius r is:

$$I(r,z) = p_{Ot} \left(\frac{2}{\pi {w_0}^2}\right) \exp\left(\frac{-2r^2}{w^2(z)}\right). \tag{2}$$

At the receiver, a photo-sensitive diode is used to generate a current when light hits its surface area. If the receiving surface of the photo-sensitive diode S is sufficiently small, then the intensity is approximately constant. Thus, the received power is

$$p_{Or} = I(r,z)S. \tag{3}$$

Assuming the optical signal is modulated using binary on-off keying, then the FSO channel capacity can be shown to be approximated by a well-known binary symmetric channel where the error probabilities $P(1|0)$ and $P(0|1)$ are equal. The noise is assumed to be Gaussian. Denote the mean and variance when i is transmitted as μ_i and σ_i, respectively $(i = 0, 1)$, then

$$\mu_0 = 0 \qquad \mu_1 = I_{out} \tag{4}$$

$$\sigma_1 = \sqrt{{I_d}^2 + {I_s}^2 + {I_{nep}}^2} \qquad \sigma_0 = \sqrt{{I_d}^2 + {I_{nep}}^2}. \tag{5}$$

I_d denotes the dark current, I_s denotes the shot noise introduced by the received power, and I_{nep} denotes the noise calculated from the noise equivalent power (NEP) of the receiving device, including the thermal noise and the shot noise resulted from the dark current. I_{out} denotes the output current of the receiver due to the received optic power given the responsivity of the receiver, R_D:

$$I_{out} = p_{Or} R_D. \tag{6}$$

In practice, $I_d >> I_s$ and $I_d >> I_{nep}$. Thus, $\sigma_1 \approx \sigma_0$. Since the bit error rate is only a function of σ, $P(1|0) \approx P(0|1)$. Approximately, this is a binary symmetric channel (BSC) with error probability P, and thus the channel capacity is:

$$C = 1 - H(P) \qquad P = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \qquad Q = \frac{\mu_1}{\sigma_1 + \sigma_0}. \tag{7}$$

Given B_{FSO}, the maximum modulated frequency of an LED, the FSO channel capacity is:

$$C_{FSO} = B_{FSO}(1 - H(P)). \tag{8}$$

3.2 RF Channel Model

The RF channel is assumed to be Gaussian with the capacity calculated as:

$$C_{RF} = B_{RF} \log_2(1 + \frac{p_{RFr}}{p_{noise}})\ bit/s, \tag{9}$$

where p_{RFr} denotes the received RF signal power. With IEEE 802.11b/g, the bandwidth B_{RF} for a single band around $2.4GHz$ is $22MHz$. The relationship between p_{RFr} and the transmitted power p_{RFt} is described by the Friis formula:

$$\eta = \frac{p_{RFt}}{p_{RFr}} = G_0 G_1 \left(\frac{\lambda}{4\pi d}\right)^n, \tag{10}$$

where G_0 and G_1 denote the gains of transmit and receive antennas, respectively. λ denotes the transmitted wave length, d denotes the distance between the transmitter and receiver. n is set to 2 for indoor environments.

4. POWER ALLOCATION OPTIMIZATION

We formulate the problem of allocating power to each LED transmitter (FSO channel) and the AP (WiFi channel) to maximize the channel capacity subject to a fixed power budget. We show that the optimal solution to the power allocation optimization problem can be approximated well using convex optimization techniques. The reason for using convex optimization framework is that there exist many efficient algorithmic solutions for convex problem. We start with a scenario of single receiver that receives data from both FSO and WiFi channel simultaneously. Let us consider a single user with access to both FSO and WiFi channel. The total channel capacity is:

$$C_{total} = C_{FSO} + C_{RF}. \tag{11}$$

Note that C_{FSO} and C_{RF} are functions of p_{Ot} and p_{RFt}, the transmitting power levels for FSO and WiFi channels, respectively. Our optimization problem is therefore:

$$\begin{aligned} \text{maximize:} \quad & f(p_{Ot}, p_{RFt}) = C_{FSO} + C_{RF} \\ \text{subject to:} \quad & p_{Ot} + p_{RFt} \le p_{total} \\ & 0 \le p_{Ot} \le p_{Ot,max} \\ & 0 \le p_{RFt} \le p_{RFt,max}, \end{aligned} \tag{12}$$

where $p_{Ot,max}$, $p_{RFt,max}$ and p_{total} denotes the maximum transmission power of the LED, the AP, and the total power budget, respectively.

We have the following proposition regarding the convexity of $f(p_{Ot}, p_{RFt})$ [8].

PROPOSITION 1. *1) $C_{RF}(p_{RFt})$ is concave; 2) There exists a small positive constant p_0 such that $C_{FSO}(p_{Ot})$ is concave for $p_{Ot} > p_0$; 3) Consequently, since $f(p_{Ot}, p_{RFt}) = C_{FSO}+C_{RF}$ is the sum of two separable functions, $f(p_{Ot}, p_{RFt})$ is concave in both p_{RFt} and p_{Ot} provided that $p_{Ot} > p_{Or,0}$ for some small constant $p_{Or,0} \ge 0$.*

Based on the Proposition 1, the objective function $f(p_{Ot}, p_{RFt})$ can be approximated by a concave function. Specifically, we replace $C_{FSO}(p_{Ot})$ with $C'_{FSO}(p_{Ot})$ such that:

$$C'_{FSO}(p_{Ot}) = \begin{cases} ap_{Ot} + b, 0 \le p_{Ot} < p_0 \\ C_{FSO}(p_{Ot}), p_0 \le p_{Ot} \le p_{Ot,max} \end{cases} \tag{13}$$

The constant a, b and p_0 can be determined $C'_{FSO}(0) = 0$ and $\frac{d}{dp_{Ot}} C'_{FSO}(p_0) = a$. With the replacement of C'_{FSO}, we approximate the original problem with the following convex problem:

$$\begin{aligned} \text{maximize} \quad & C'_{FSO}(p_{Ot}) + C_{RF}(p_{RFt}) \\ \text{subject to:} \quad & 0 \le p_{Ot} \le p_{Ot,max} \\ & 0 \le p_{RFt} \le p_{RFt,max} \\ & p_{Ot} + p_{RFt} \le p_{total}. \end{aligned} \tag{14}$$

Now let us consider multi-user scenario. Let $\boldsymbol{p_{Ot}} \in \boldsymbol{R}^N$ and $\boldsymbol{p_{RFt}} \in \boldsymbol{R}^N$ denote the transmitted power vectors for FSO and RF channel. $p_{Ot,i}$ and $p_{RFt,i}$, the ith elements of $\boldsymbol{p_{Ot}}$ and $\boldsymbol{p_{RFt}}$ denote transmitted powers on FSO and RF channels for user i, respectively. The multi user optimization problem is to find the FSO and WiFi power allocation for each users in order to maximize the total capacity of all the users subject to a given power budget. It can be formulated as:

$$\begin{aligned} \text{maximize:} \quad & \phi(\boldsymbol{p_{Ot}}, \boldsymbol{p_{RFt}}) = \textstyle\sum_{i=1}^N \left(C'_{FSO,i} + C_{RF,i}\right) \\ \text{subject to:} \quad & \textstyle\sum_{i=1}^N (p_{Ot,i} + p_{RFt,i}) \le p_{total} \\ & 0 \le p_{Ot,i} \le p_{Ot,max}, i = 1, 2, ..., N \\ & 0 \le p_{RFt,i} \le p_{RFt,max}, i = 1, 2, ..., N, \end{aligned} \tag{15}$$

where N denotes the total number of users.

Convexity: Because $\phi(\boldsymbol{p_{Ot}}, \boldsymbol{p_{RFt}})$ is a sum of concave functions, it is concave. So the approximate problem is a convex problem with linear constraints.

Algorithm. Given the analytical expression above, we can compute the gradient, and use a standard projected gradient to solve the constrained convex problem above [8].

5. SIMULATION RESULTS

We show the simulation results for the WiFiFO system under typical settings. All receivers are placed $5m$ below their FSO transmitters. The radius of the optical cone is set to be 1.5m, i.e., $0 \leq r \leq 1.5$. The optoelectronic devices used for transmitter and receiver are the LED (LED815L), LED driver (MAX3967A), photodiodes (FDS-100) and transimpedance amplifier (MAX3665). Next, all transmitters are placed within the range of $20m$ to the RF transmitter. $B_{RF} = 22Mhz$, $p_{RFt,max} = 100mW$. We assume that all the FSO transmitters are connected to a 100 Gbits Ethernet. As a result, the WiFiFO network can theoretically support up to 200 users with 50 Mbps for each user using only FSO transmissions. Effectively, the total bandwidth for FSO is very large, however, the capacity is limited by the power consumption of the LEDs.

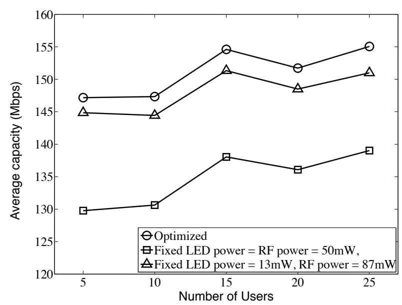

Figure 2: Capacity vs. number of users

Figure 2 shows the average capacity per receiver vs. the number of receivers. The number of receivers are 5, 10, 15, 20, and 25. The average capacity is calculated as

$$C_{ave} = \frac{1}{N} \sum_{i=1}^{N} [C_{FSO}(\hat{p}_{Ot,i}) + C_{RF}(\hat{p}_{RFt,i})] \qquad (16)$$

The result of optimization is compared with two other uniform power allocations: 1) Each LED transmitter is allocated 13 mW, which is a typical value for the LED transmitter; b) The power for each transmitter is equally allocated, i.e., all LED and RF transmitters get 50mW. As seen in Figure 2, the power allocation resulted from the proposed algorithm outperforms those of other two power allocation schemes for all 5 cases.

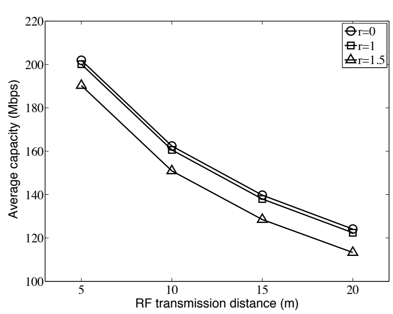

Figure 3: Capacity for different values of r;

Next, to simulate the effect of changing the RF and FSO transmission distances on the capacity, we perform the following simulations. In this setup, all ten receivers are located at a fixed distance ($r = 0, 1, 1.5$ meters) to the center of the beam. In addition, for each r, we vary the RF transmission distances to receivers from 5 to 20 meters with 5 meter spacing. Figure 3 shows the achievable maximum capacity with different values of r and the RF transmission distances. As expected, as the RF transmission distance increases, the average capacity per receiver decreases. Also, a larger r results in smaller average capacity as expected. We note that the simulation results indicate that the ideal throughput *per user* can range from 120 Mbps to 200 Mbps. This is an order-of magnitude increase in capacity compared to the existing WiFi networks. The primary reason for this significant increase is due to additional bandwidth provided by FSO transmissions under the assumption that these LED transmitters are connected to a 100 Gbps LANs. If the LED is connected to a 10 Gbps, then the capacity gain is less due to the bottleneck of the LAN. However, we should expect a significant capacity gain over the existing WiFi networks.

6. CONCLUSION

This paper presented a mathematical model and an algorithm for maximizing the joint capacity of the proposed indoor WiFi/FSO system (WiFiFO). A multi-user channel capacity optimization problem respect to the transmitted power is studied. Simulation results show significant increase in the capacity over the existing WiFi networks.

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