A Cell-Free Networking System With Visible Light

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***Abstract*— LED luminaries are now deployed densely in indoor areas to provide uniform illumination. Visible Light Communication (VLC) can also benefit from this dense LED infrastructure. In this paper, we propose DenseVLC, a cell-free massive MIMO networking system enabled by densely distributed LEDs, that forms different beamspots to simultaneously serve multiple receivers. This is a cell-free system, as there is no notion of autonomous cells and transmitters cooperate to jointly serve the users. Given a power budget for communication, DenseVLC assigns the power budget among the distributed LEDs to optimize the system throughput and user fairness. We formulate an optimization problem to derive the optimal policy for the power allocation. Our insights from the optimal policies allow us to simplify DenseVLC's system design and propose a heuristic algorithm that can reduce the complexity by 99.96%. Besides, we propose a novel synchronization method using non-line-of-sight VLC to synchronize all the transmitters that will form a beamspot to serve the same receiver. We implement DenseVLC with off-the-shelf devices, solve practical challenges in the system design, and evaluate it with extensive and realistic experiments in a system of 36 transmitters and 4 receivers in an area of 3 m × 3 m. Our results show that DenseVLC can improve the average system throughput by 45%, or improve the average power efficiency by 2.3 times, while maintaining the requirement for uniform illumination. Finally, we demonstrate that DenseVLC is robust against blockage.**

***Index Terms*— Visible light communication, cell-free, networking, massive MIMO, over-the-air synchronization, blockage, implementation, evaluation.**

I. Introduction

ARTIFICIAL illumination consumes about 20% of the world's electricity and produces carbon emissions that are comparable to the global automobile fleet [2]. To reduce this high energy consumption, traditional fluorescent and incandescent bulbs are being replaced by energy-efficient LEDs [3]. Deploying LEDs is not only beneficial for illumination, but also enables Visible Light Communication (VLC) to piggyback on LED's illumination [4], [5]. Yet, the primary function of an LED remains illumination. To increase user comfort, uniform illumination has become an essential requirement in advanced lighting systems. However, due to the well-known Lambertian propagation property of LEDs, it is challenging to illuminate a large area uniformly and efficiently with a single LED [6]. To tackle this problem, deploying LEDs in arrays was proposed in [7] and has been investigated extensively to obtain uniform illumination [8]–[10].

With this dense-luminaries infrastructure, new techniques for communication have been explored to exploit the LEDs' spatial diversity by enabling the Distributed Multiple-Input-Multiple-Output (D-MIMO) in VLC networks [11]–[13]. In these previous works, all the LEDs are synchronized to increase the received signal strength at the receiver. However, these works are highly energy inefficient. As saving energy is the key reason for deploying LEDs for illumination, it is essential that (1) VLC incurs limited extra power, and (2) no power is wasted. The above works do not satisfy these requirements, as all LEDs send the same data to a receiver and consume the same amount of power, even if they do not contribute equally to the performance improvement at the receiver. To improve the power efficiency in D-MISO VLC, recent works have proposed new precoding schemes to serve multiple users [14], [15]. However, these past works are purely based on simulations, only consider limited number of transmitters, static receivers and make simplistic assumptions for the synchronization among the LEDs.

Recently, researchers in Bell Labs proposed the concept of Cell-Free Massive MIMO (CFM-MIMO) in [16]. In such a system, a large number of distributed, low-cost, and low power access point antennas are connected to a controller to serve a much smaller number of users. The proposed system is not partitioned into cells anymore and all the users are simultaneously served by all LEDs within the receiver's field of view. This facilitates mobility and improves the dynamic performance, compared to the conventional small cell-based design [17]. CFM-MIMO has now attracted increasing attentions from the massive MIMO society, and has been proved to improve greatly the system performance in terms of outage rate, system throughput, and so on [18]–[21].

Inspired by this disruptive concept, in this paper we propose, design and implement the *DenseVLC*, a practical CFM-MIMO networking system enabled by densely distributed LED luminaries. With the intrinsic characteristics of being low-cost, low power consumption, and densely distributed, DenseVLC can enable adaptive and power-efficient CFM-MIMO beamspots to serve multiple receivers simultaneously. Given the measured link qualities between the LED transmitters (TXs) and receivers (RXs), DenseVLC allocates dynamically the power

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