Welcome to the CROWD: Design Decisions for Coexisting Radio and Optical Wireless Deployments

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Abstract

Novel systems and solutions are needed to meet the ultra-dense data demand expected in future wireless networks. Heterogeneous integration of radio and OW communications is one solution that promises to add wireless capacity where it is needed most (e.g., indoor environments). These coexisting radio and optical wireless deployments, or CROWD networks, will utilize densely distributed optical small cells to supplement conventional RF small cells. The directionality of the optical small cells allows access points to be located at reasonable distances from the mobile terminals while offering coverage area on the order of $1m^2$. Accordingly, the OW network allows for ultra-dense cells, high area spectral efficiency, and high aggregate capacity. Additionally, the heterogeneous integration allows the RF small cells to provide coverage and reliability for highly mobile devices. In this work, we motivate the adoption of CROWD networks, review techniques for RF/OW coexistence, and evaluate the impact of dynamic system characteristics. In particular, we show the need for improved statistical modeling of the wireless environment at the spatial resolution of ultra-dense networks. We also highlight the role that intelligent and adaptive CROWD networks will play in accommodating the variations in traffic distribution from dynamic environments and mobile devices.

Introduction

Demand for ubiquitous wireless connectivity continues to grow due to the trend toward an "always on" culture, broad interest in mobile multimedia, and advancement toward the Internet of Everything. This demand stems from a multifaceted growth in the number of networked devices and the per-device data usage from novel applications (e.g., HD video, augmented reality, and cloud services). Next generation, or 5G, wireless networks will be challenged to provide the capacity needed to meet this demand. While earlier generations focused primarily on peak performance, 5G objectives also focus on system goals such as increasing the expected performance across non-uniform geographic traffic distributions. In particular, additional capacity is needed in dense urban environments and indoor spaces.

Multi-tier heterogeneous networks (HetNets) will play an important role in accommodating these non-uniform distributions. Traffic offloading to WiFi WLANs and other RF small cells (RFSCs) is already an established technique for opportunistically adding capacity to dense environments where macrocells are overloaded. We envision an additional tier of ultra-dense directional small cells (DSCs) that supplement RFSCs in areas such as apartment complexes, coffee shops, and offices where device density and data demand are at their highest.

WLAN technologies such as 802.11ax are beginning to address ultra-dense data demand using multi-user MIMO (MU-MIMO) and OFDMA for concurrent access with near-optimal use of the available RF resources. Our alternative vision considers densely distributed DSCs with channel isolation via directional transmission in order to supplement the RF channel with additional resources that have a high degree of spatial reuse. The added DSC tier addresses the challenge of concurrent connection to many devices while also increasing the peak aggregate capacity and area spectral efficiency in order to accommodate increasing device density and per-device data demand.

Optical wireless (OW) communication, specifically visible light communication (VLC) or LiFi, is a directional communication technology that has gained interest in recent years [1–5]. Advancements in light emitting diode (LED) technology allow for optical intensity modulation at rates far beyond what is perceivable by the human eye. Accordingly, VLC-enabled luminaries can be used as DSCs with dual-use for both illumination and data communications. Indoor free space optics (FSO) systems have also been introduced in the context of ultra-dense OW networks [6, 7]. These systems incorporate pencil-beam emission, tracking, and beam adaptation.

Recently, OW research has shifted toward network and system deployments. Much of the system level work has analyzed potential performance gains from RF/OW HetNets where the two access technologies coexist within the same environment [8–14]. Figure 1 depicts scenarios where such a Coexisting Radio and Optical Wireless Deployment, or CROWD, has the potential to provide much needed additional capacity within dense multi-user environments. While

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recent articles discuss aspects of OW networks and RF/OW HetNets, we aim to provide a broad system view of the challenges and opportunities related to CROWD networks, ranging from their deployment within broader multi-tier HetNets to their optimization under dynamic environment conditions and implementation of context-aware CROWDs.

Our work in [12] motivates the integration of LiFi within the next generation lighting and communication infrastructures. In [13], we describe a proof-of-concept WiFi/LiFi HetNet. In this article, we introduce CROWD networks, review motivating factors and implementation techniques for RF/OW HetNets, and analyze the impact of dynamic characteristics on network performance. The resulting analysis motivates further research into intelligent/adaptive CROWDs, and the need for detailed statistical models of wireless devices at the spatial resolution of ultra-dense wireless networks. Moreover, we present a tutorial-style overview of CROWD networks and highlight challenges that are currently being addressed along with research opportunities that are ripe with potential.

In the following section, 5G trends are discussed in order to motivate CROWD networks. Then we provide a system level view and comparison to macrocell/RFSC HetNets. Following that we describe deployment considerations and CROWD dynamics. We then define RF/OW coexistence techniques and evaluate the impact of time-varying environment characteristics. The final section concludes the article.

Motivation

Network densification can significantly improve aggregate wireless capacity [15]; however, decreasing the coverage area and increasing the density of conventional RFSCs leads to infrastructural constraints regarding access point (AP) distribution and connectivity. For example, ultra-dense deployment of conventional RFSCs is restricted by the need to locate APs in close physical proximity to the mobile terminals (MTs); however, a DSC's coverage is determined by both transmit power and emission pattern. Accordingly, *directionality allows DSC APs to be deployed at reasonable distances from the MTs* while still providing a small coverage area at the working surface.

While directional emission mitigates the physical constraint on AP deployment, the access network can still be cost prohibitive in ultra-dense distributions. Luckily, the growing adoption of network controlled LED lighting systems offers an available infrastructure that is well suited to provide densely distributed communications. Many lighting systems implement power line communication or power over Ethernet, and *shared use of this infrastructure will reduce the wired access network cost for distributed DSC APs*. Such use of a shared lighting and communication infrastructure has precedent. RFSCs integrated within network connected smart street lights utilize a shared access network and offer an added service that distinguishes the street lights from competitors' products (website: www.ericsson.com/ourportfolio/networks-products/lightpole-site).

Given that typical environments encounter a variety of MTs and that MT use cases change over time, wireless access technologies of various coverage range and spectrum use must coexist for improved aggregate performance. *RF/OW coexistence offers aggregate capacity gains via densely distributed OW DSCs while adding the RFSC's reliability and coverage*. Accordingly, CROWDs have the potential to improve indoor[1] wireless access in ultra-dense environments.

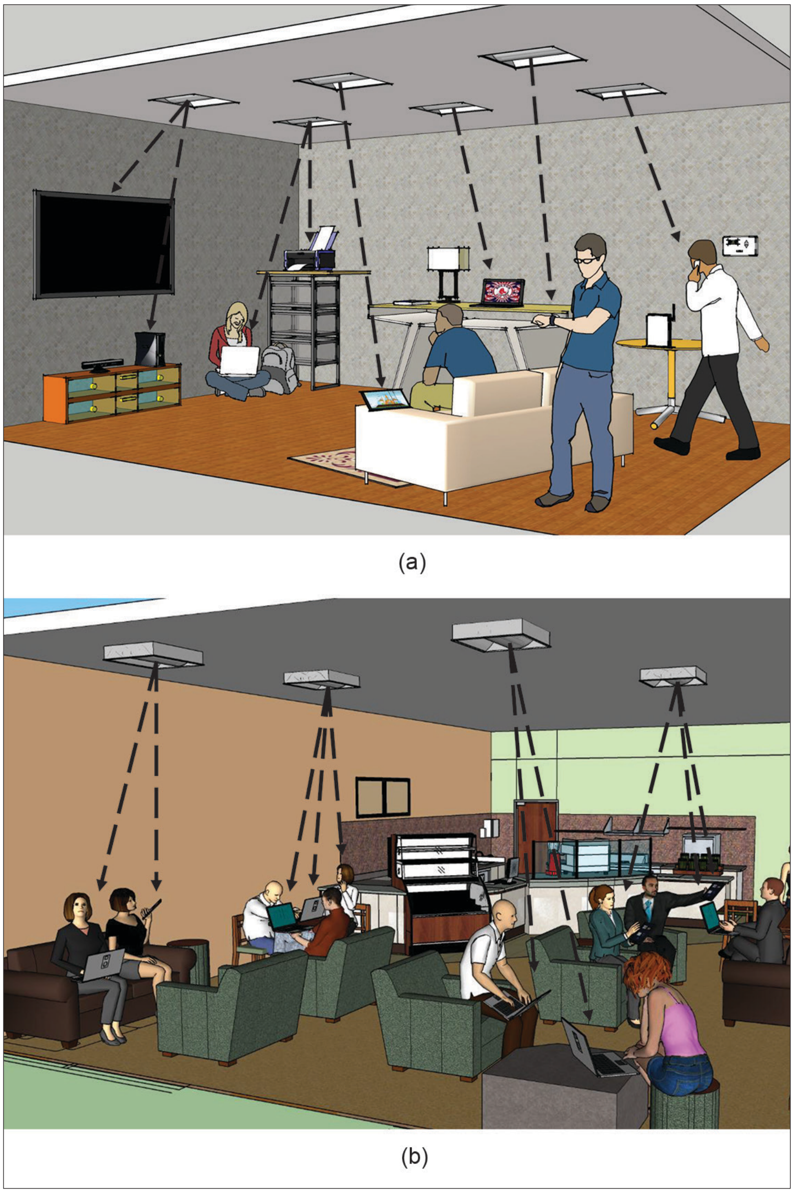

FIGURE 1. Optical wireless directional small cells (DSCs) providing additional wireless capacity in a) an apartment and b) a coffee shop.

System View

Indoor CROWDs are envisioned as RF/OW HetNets that provide lower tier network access within multi-tier HetNets. Under the coverage of a Macrocell, RFSCs of various coverage area and access technologies allow traffic to be offloaded to the RFSC tier. CROWDs allow for further offloading from RFSCs to the OW DSC tier. Figure 2 depicts a broad view of the wireless ecosystem showing five CROWDs and other RFSCs within a Macrocell. Two specific CROWDs are called out in order to demonstrate the CROWD basic service set (BSS).

[1] RF/OW coexistence has been explored for outdoor access networks with high speed backhaul connectivity via FSO and mmWave or other RF media as a backup. While this topic fits within the realm of CROWD networks, we specifically focus on the indoor use case for end user access.

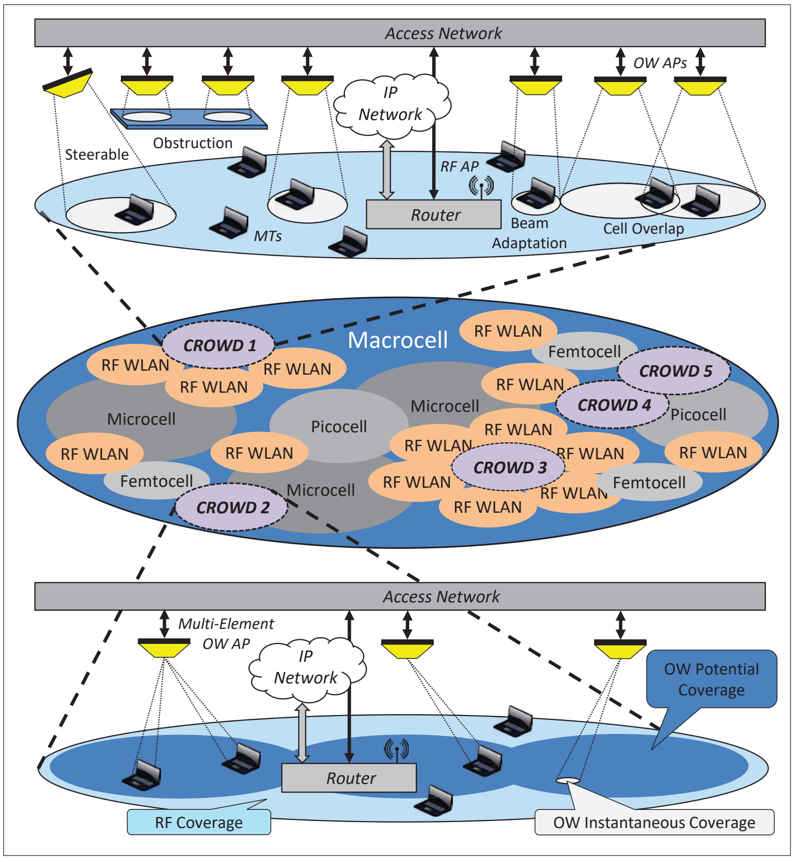

FIGURE 2. Proposed CROWD network in the context of a multi-tier HetNet with various RFSCs. The callout above depicts a basic service set for a CROWD incorporating an RFSC and multiple OW DSCs implementing VLC. The callout below shows a second CROWD implementing multi-element OW transmitters with narrow emission and dynamic beam width / beam angle.

CROWD Components

The CROWD BSS consists of an RFSC AP, one or more OW DSC APs, MTs, an access network, a router and/or central controller (i.e., CROWD Control), and an external gateway. OW APs may also have multiple transmission elements (e.g., beams in the indoor FSO scenario). This infrastructure adds the OW DSC tier to a traditional RF WLAN BSS, providing additional capacity and mitigating RF congestion by offloading traffic to OW DSCs. The RFSC is available for highly mobile devices and MTs without a reliable OW connection. Similar to RFSC deployment in high traffic areas within the macrocell, OW DSCs should be deployed in a way that places OW "hotspots" at high traffic locations under the coverage of the RFSC (e.g., desks at home or offices and sitting areas at coffee shops).

CROWDs within the 5G Ecosystem

Within the macrocell in Fig. 2, the lower left CROWD (i.e., CROWD 2) is relatively isolated; therefore, the primary benefit of the OW tier is to add capacity and increase area spectral efficiency in a dense high traffic area. CROWD 3 is surrounded by RF WLANs; therefore, offloading traffic to the OW DSCs not only adds capacity and reduces traffic on the CROWD's RF channel, but also mitigates RF interference to neighboring WLANs. CROWDs 4 and 5 are deployed with overlapping RF coverage. Here, directed emission and the OW channel's susceptibility to blocking make the effect of the OW signals from neighboring CROWDs negligible, even without coordination between the CROWDs.

Comparison to Macrocell/RFSC HetNets

CROWD implementation shares similarities with macrocell/RFSC HetNets; however, significant differences arise when considering the directionality and spatial resolution of the DSC tier. System characteristics at this level of observation lead to novel challenges and research opportunities.

Network Control and Ownership: Macrocell APs are owned and controlled by a global entity (i.e., service provider). Therefore, interference can be mitigated in the provisioning process. RFSCs are purchased by local entities (i.e., home/business owners) and are often deployed in an ad-hoc manner such that interference is not planned. The novelty of densely distributed DSCs is that AP layout is controlled by a local entity and interference between DSCs controlled by neighboring entities is negligible. Therefore, provisioning of the lower tier DSCs can be evaluated locally. Similarly, dynamic control (e.g., resource allocation, beam adaptation, handover) can be locally coordinated and network authentication can be handled across tiers. This coordinated local deployment has similarities with high density WLAN deployments in universities and businesses where layout and connectivity are part of the building infrastructure design. While macrocell/RFSC HetNets have a planned higher tier and ad-hoc lower tier, the opposite is true for CROWDs, allowing the OW DSC deployment and operation to be optimized.

Spatial Scale and Resolution: Small coverage area and dense distribution improves area spectral efficiency (b/s/Hz/m^2) and aggregate capacity, but smallness also increases the difficulty of maintaining seamless connectivity for mobile devices. Assuming that DSCs have coverage area on the order of 1m^2, translational motion can cause drastic channel variations at a relatively fast time scale. Accordingly, use cases where device users are walking through an environment can significantly impact system performance. For example, prioritizing the DSC network can degrade performance if MTs move quickly relative to the handover latency. Using DSCs primarily for MTs operating in a relatively static position can mitigate mobility constraints. These quasi-static MTs (i.e., wireless devices such as laptops/tablets that are often used in a stationary position) are common sources of high data rate traffic. Therefore, offloading fixed position wireless traffic to DSCs can free a large portion of RFSC resources.

Lower Tier Directionality: Compared to macrocell/RFSC HetNets, the directionality of the DSC APs introduces challenges related to characteristics of the MT's orientation and rotational motion. Given the significant impact that emission and acceptance angles have on signal strength, the effect of orientation implies that an AP's Quality of Service (QoS) is not directly related to the proximity of an AP to the MT. This implies that a DSC's 'coverage' relates to the MT's location *and orientation* (Fig. 3). Interference and resource allocation are also impacted by directionality since the set of DSC APs within a MT's field of

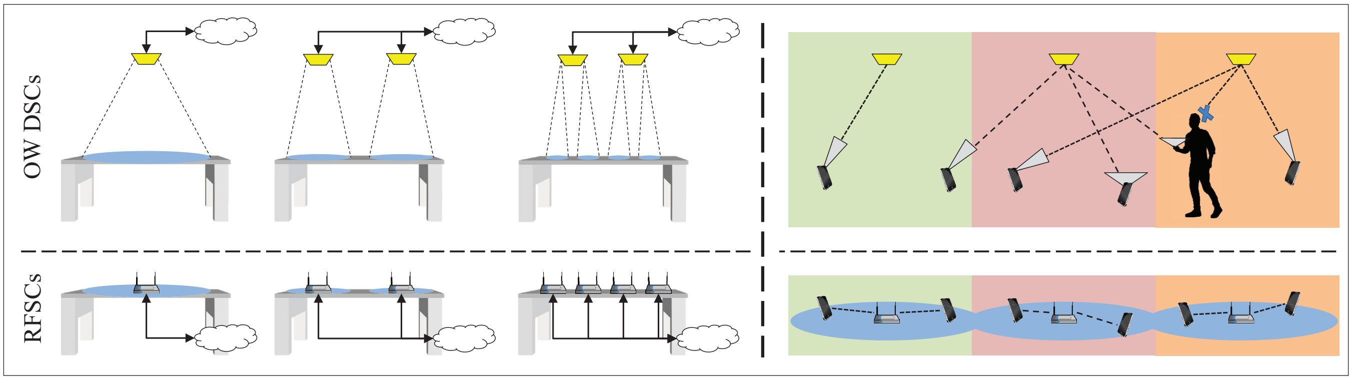

FIGURE 3. Novel characteristics of the directional small cell tier related to the OW channel's directionality and susceptibility to blockage. The left images show how AP directionality provides dense cell deployment by narrowing emission angles, allowing the system to keep APs and the associated infrastructure at a reasonable distance from the working surface. The right images show how MT directionality and blocking conditions abstract the relationship between physical proximity and quality of service. Colors indicate physical proximity and dashed lines indicate connectivity. Cones attached to the MTs indicate field-of-view.

view (FOV) is dependent on the MT's orientation. Additionally, the time scale of channel variations for rotational motion is much smaller than that of translational motion. Given the impact of mobility and directionality, context-aware CROWDs have the potential to improve system performance by incorporating the context of use into decision processes at the control plane.

Optical Channel Occlusions: Occlusions of the optical channel must be accounted for when the DSC tier implements OW communications. This includes modeling both the frequency and duration of occlusions. These models should also incorporate both random occlusions and occlusions that may occur due to obstruction of the MT's line-of-sight (LOS) path by an associated user. The key difference is that opaque objects obstructing the LOS path will cause a complete loss of an OW signal (i.e., blockage) [16]. This is contrary to most RF scenarios where objects absorbing energy will degrade the signal and decrease SNR, but complete signal loss is dependent on the noise floor. The potential for LOS obstructions between the MT and nearby APs further abstracts the relationship between proximity and QoS on the lower tier (Fig. 3).

Deployment Challenges and Considerations

A CROWD's aggregate performance gains depend on deployment characteristics of the RF and OW networks. The local ownership of the OW network provides an opportunity for the deployment and control of the DSC tier to be optimized along with the interaction between the CROWD's RFSC AP and the DSC tier. Furthermore, the network's dynamic capabilities allow the CROWD to adapt to the time-varying characteristics of the environment and MTs.

Layout and Provisioning

When provisioning a CROWD, there are tradeoffs in the decisions for parameters related to the OW network, the RFSC access technology, and the access network. The impact of a specific parameter is also often dependent on other network parameters. A subset of *provisioning parameters for the OW tier* are described below.

OW AP Layout: The number of OW APs and their location within the CROWD will impact the OW tier's utilization and overall network performance. Grid or hexagonal lattice structures have been explored; however, selective placement can also improve performance. Uniform likelihood of a MT being at any location is often assumed, but realistically, selective placement of OW DSCs can opportunistically locate hotspots at high traffic areas (e.g., desks and workstations) or near the RFSC edge to enhance coverage.

OW Emission Pattern: OW DSC technologies can range from broad emission luminaires to pencil-beam, or indoor FSO, transmitters. Broad emission transmitters provide better ability for receivers to acquire a signal, but a small portion of the emitted OW power is received. Broad emission VLC transmitters are therefore often considered for dual-use so that the emitted optical power that is not used for communication is still effectively utilized for illumination. Pencil-beam transmitters mitigate interference and have a higher utilization of the transmitted power, but require precise alignment.

OW Receiver Implementation: Receiver architectures have been proposed ranging from wide to narrow FOV, line-of-sight and diffuse, single pixel and multi-element (e.g., diversity and imaging receivers), etc. These decisions significantly impact the OW interference and outage probability. Receiver implementation could conceivably be defined for a given system; however, it is feasible that MTs with various OW receiver configurations could attempt to access the OW network. In a CROWD, MTs with incompatible OW receiver architectures would still have access to the RFSC.

Modulation, Coding, and Resource Allocation: Modulation and coding scheme (MCS) selection will impact link and aggregate performance in ultra-dense multi-cell/multi-user CROWDs. MCS selection also defines how resources (e.g., time, frequency, wavelength, and so on) can be allocated across neighboring APs and/or MTs. In multi-element DSCs, scheduling is required for the individual elements. Furthermore, select resources may be allocated for non-communication functionality (e.g., localization, motion tracking, AP identifiers, and so on).

OW Multi-Element Capabilities: OW DSCs may implement independent OW connections to multiple users or use synchronized transmission

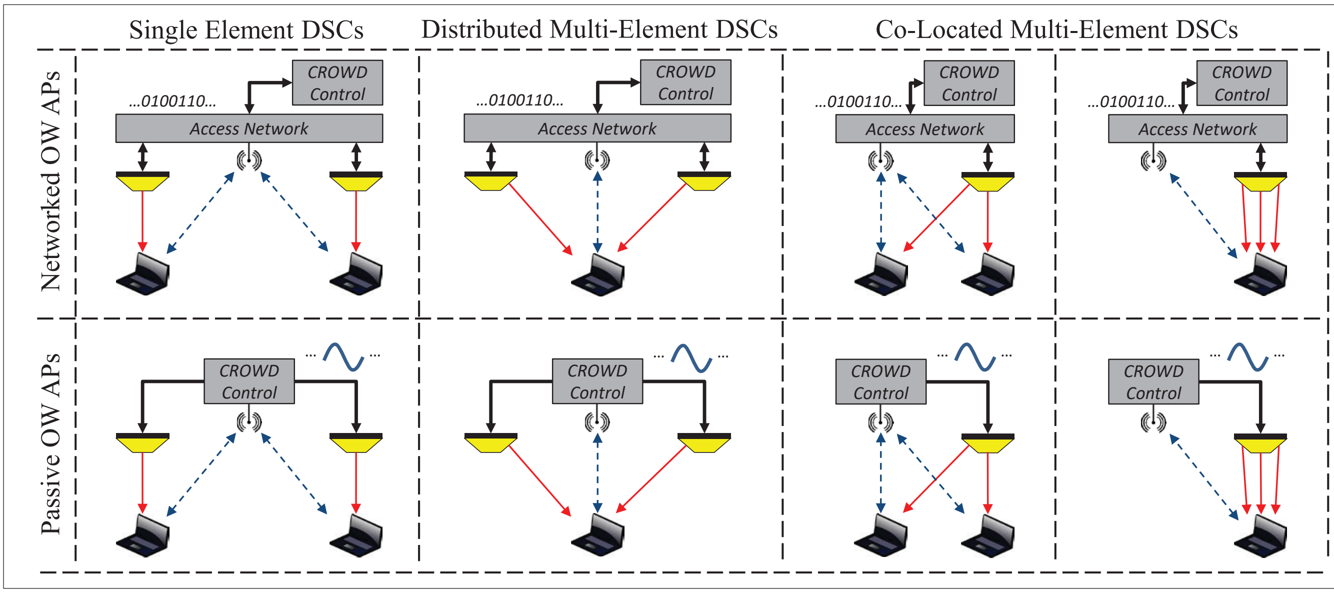

FIGURE 4. Various configurations for the OW DSC tier. The top images show networked OW APs where each AP has a bidirectional connection to the central control. The lower images show passive OW APs where power and signal generation are handled centrally (similar to RF remote radio heads). Horizontally, single-element OW DSCs are compared with distributed and co-located multi-element OW DSCs. Dynamic adaptive systems allow the network configuration to be changed from multi-user/single-element per MT implementations for high aggregate throughput (i.e., column 1 and 3) to single-user/multi-element implementations for high user throughput (i.e., columns 2 and 4). In column 2, distributed APs combine to form a single multi-element OW DSC.

elements for increased single user throughput (Fig. 4). Multi-element systems may utilize co-located elements or distributed elements to implement coordinated multi-point (CoMP), MIMO, or spatial modulation. When OW APs are jointly utilized, coordination is required. AP coordination may be implemented via synchronized access network connectivity across the distributed elements or in a way where a central coordinator sends analog drive signals such that individual elements act as passive OW antennas.

OW Uplink: If in-band uplink is not practical, asymmetric connections can implement different access technologies for uplink and downlink. This includes asymmetric OW connections (e.g., VLC downlink and IR uplink) as well as asymmetric RF/OW connections (e.g., OW downlink and WiFi uplink). If the OW network connection's uplink channel utilizes the same resources as the RFSC, the benefit of offloading to an OW connection will be dependent on the distribution of uplink and downlink traffic. For example, offloading video streaming traffic would have more impact than offloading traffic from a MT that is uploading large files to cloud storage.

Cost and Complexity Considerations: System deployment cost and the complexity of both human interaction and system design are of importance when provisioning a CROWD. As AP density increases, the cost of individual APs typically decreases due to economies of scale; however, the access network cost tends to increase. As mentioned earlier, one benefit of co-locating APs with lighting is the potential for a shared access network. Regarding operational cost, energy comparison is of high importance. An added benefit of the dual-use VLC paradigm is that energy usage for communications only relates to the *difference* between the VLC system and a conventional non-VLC lighting system. In terms of complexity, provisioning should account for the need to coordinate and configure the system based on dynamic conditions (discussed in the following sections).

Dynamic Environment Characteristics

Today's wireless ecosystem is such that common MTs are highly dynamic in their usage. This includes variations in data demand, traffic symmetry (i.e., uplink/downlink), and physical properties (e.g., rate of translational/rotational motion, frequency and duration of occlusions, and the number of devices accessing the network). In a CROWD, the relationship between physical usage and data demand can have a significant impact on whether a MT is better suited for the RF or OW connection (Fig. 5). Statistical properties of these dynamics are also time-varying and are related to both the type of device and the application(s) in use.

Consider two extreme scenarios for smartphone usage: (*S*1) sitting at a table while streaming a video, and (*S*2) walking down a hallway while messaging in a text-based application. It is easy to imagine that offloading to the OW tier has more impact in *S*1. However, consider a third scenario where the MT from *S*2 is being used in a video chat. Here, the high data demand would be preferably offloaded to the OW tier; however, the motion would imply frequent handover requirements due to the OW DSC's small coverage area. This example shows how understanding the relationship between data usage, mobility, and device type is key to optimal selection of access technology.

The context of use also applies to the environment in which the CROWD is deployed since traffic distribution throughout a space is time-varying and varies from one space to another. Similarly, the statistical relationship across devices in such a

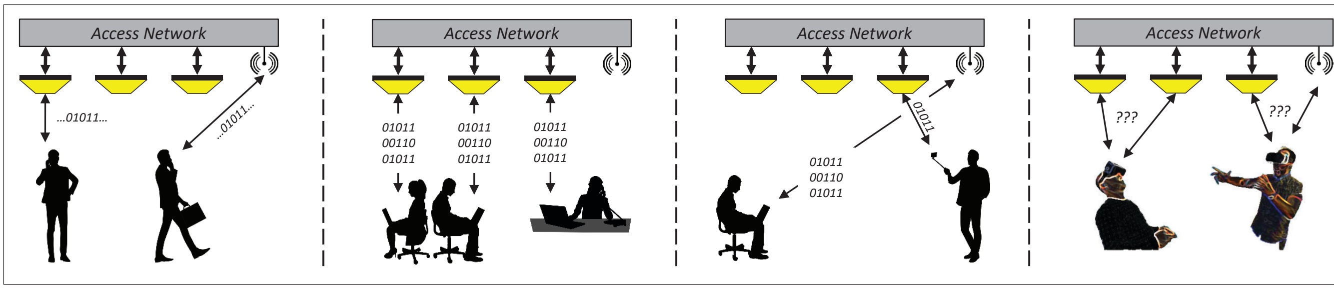

FIGURE 5. Optimal distribution of traffic between the RFSC and the OW DSC tier should account for the context of use. Such context aware CROWDs may observe the data demand, traffic patterns, device type and/or application. Additionally, physical usage such as translational or rotational motion and frequency or duration of OW occlusions can aid in the resource allocation decisions. Furthermore, intelligent CROWDs should be aware of the system-wide usage as network association preferences may depend on the relative usage of each tier by other MTs (i.e., congestion). Optimal decisions for highly mobile high rate scenarios such as AR/VR will be significantly impacted by handover latencies.

dense environment can play a part in the analysis of practical systems.

Dynamic CROWD Network Configuration

When the CROWD infrastructure is physically static, dynamic environments can be accommodated through network configuration. A subset of *network configuration techniques* are described below.

Handover: As MTs move throughout an environment, their network connection and the specific AP or APs that they associate with must be dynamically configured. For MTs in a CROWD, this includes horizontal handover (HHO) across OW DSCs and vertical handover (VHO) between the RF and OW tiers. At the two extremes, the following techniques can be observed:
- Pure HHO where MTs only use the OW network
- Required VHO where a MT that loses its OW connection must switch to the RFSC before associating with another OW DSC.

The optimal handover solution falls somewhere in between such that MTs are opportunistically assigned based on the device characteristics (e.g., context of use, data demand, and so on), network conditions (e.g., VHO/HHO latencies), and system characteristics (e.g., RF/OW energy comparison).

Adaptive MCS and Resource Allocation: Given the OW channel's variability, CROWDs can adapt the MCS and distribution of resources to accommodate a MT's signal quality variations. This can be done at each OW AP or collectively across APs. In a CROWD, the RFSC's availability should be considered when designing adaptive MCS, interference management, and resource allocation techniques. For example, when a MT associated with an OW AP experiences signal degradation, reducing the OW throughput may not be optimal. It may be preferable to switch the MT to the RFSC and have a different MT on the RFSC switch to the OW DSC.

Dynamic CROWD Physical Configuration

Added flexibility improves a CROWD's ability to adapt to environment dynamics. However, appropriate use of the dynamic capabilities also requires additional sensing, system intelligence, and other overhead that impacts the system cost and complexity. A subset of *dynamic physical capabilities* are described below.

Beam Adaptation: OW emitters that can dynamically modify beam width and/or beam angle allow CROWDs to adapt their DSC's coverage regions to the device/traffic distribution and mitigate outage conditions due to blocking. This is depicted in the top callout of Fig. 2 where the MT on the left would have been under the coverage of the second OW AP from the left. Since the MT is shadowed by the obstruction, the otherwise unused OW AP on the far left is redirected. Beam adaptation is essential in the case of indoor FSO DSCs since tracking and steering are needed to provide reasonable coverage. The bottom callout of Fig. 2 depicts the difference between instantaneous coverage of a controllable emission DSC and the potential coverage over the set of possible emission patterns [6]. For dual-use VLC APs, dynamic emission VLC APs must carefully avoid negative effects to the room illumination.

Receiver Adaptation: Adaptive receivers may incorporate dynamic optics, steerable photosensors, and spatial light modulators. As with the receiver architecture, specific adaptive receiver capabilities may be included in the design of the system while offering RFSC access to MTs with incompatible OW receivers.

RF/OW Coexistence

OW technologies continue to advance and novel RF/OW integration techniques have been proposed. However, many research opportunities still exist related to the shift from coexistence to full cooperation (i.e., HetNets where technologies and resources are intelligently allocated to handle the traffic and use-cases that they are best suited to serve). We describe various coexistence techniques and develop a model to show how characteristics of the system dynamics impact the relative performance gain of different techniques.

RF as a Fallback Technology

The spatial resolution of CROWD networks leads to fast variations in the distribution of traffic throughout an environment. Rather than requiring CROWDs to perpetually accommodate the low probability peak requirements at all locations, it is fair to assume that all areas do not need maximum capacity at all times. Accordingly, CROWDs can adapt to environment variations by dynamically distributing traffic.

Use of the RF channel is an excellent example of how CROWDs can accommodate geo-

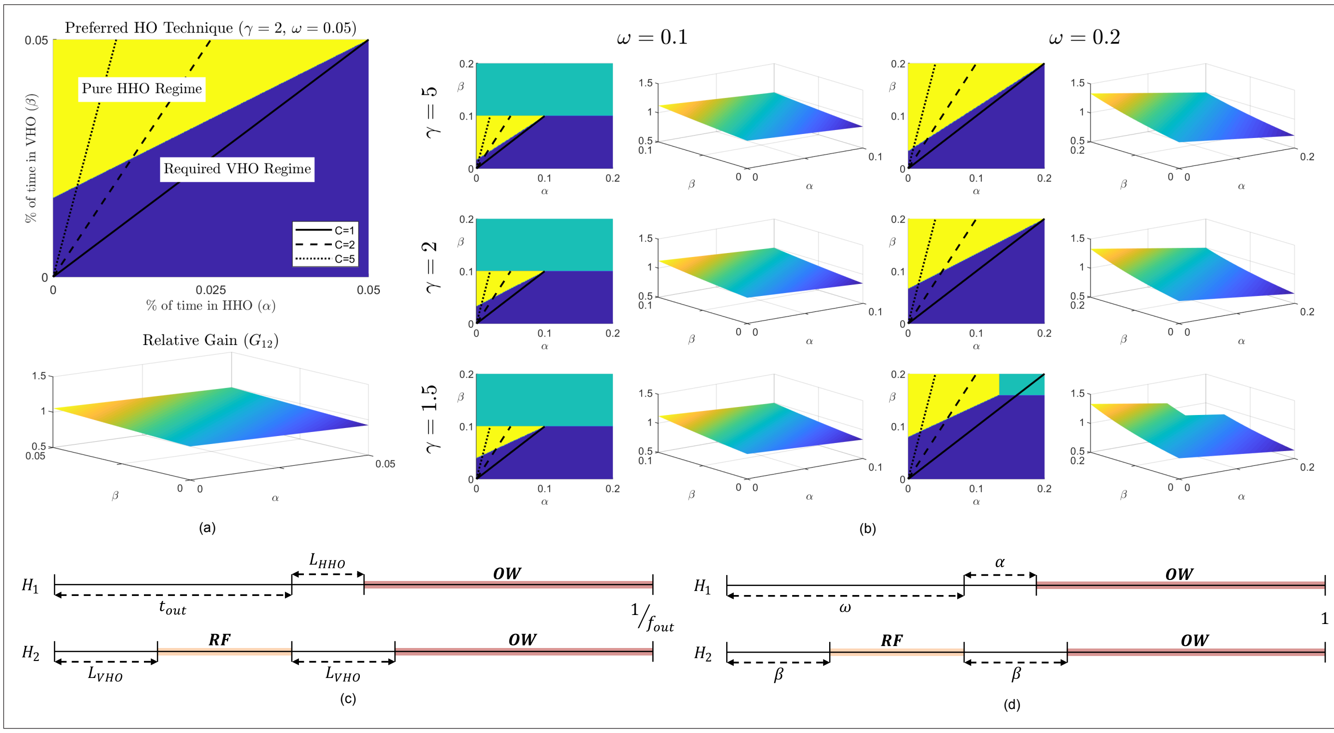

FIGURE 6. Depiction of various paradigms where different coexistence techniques provide better performance gain. Results are shown for different ratios of OW to RF capacity (γ) and percentage of time without an OW signal (ω). The 2D images show regions where the pure OW scenario (H_1) outperforms the required VHO scenario (H_2) in yellow and regions where H_2 outperforms H_1 in blue. The 3D images show the relative gain of H_1 over H_{2s}. All images show performance gains over a range for percentage of time implementing HHO (α) and percentage of time implementing a one-way VHO (β). Operational lines are also depicted to show the different crossing points depending on relative VHO/HHO latencies ($C = L_{VHO}/L_{HHO}$).

graphic demand variations. In indoor spaces, data demand commonly peaks at different locations throughout the day (e.g., where groups of individuals come together at a coffee shop or in a meeting room). Rather than providing OW coverage to meet the peak requirements, the distributed OW DSCs can provide moderate rates that accommodate a high percentage of use cases, and the RFSC can be used to achieve the peak rates at different locations as the demand distribution changes. Consider a scenario with an RF AP, two OW APs and three MTs that require 1Gb/s throughput. Assume that it is equally likely that two MTs are located in either of the OW DSCs, but it is unlikely for all three MTs to be located in the same OW DSC. The primary scenarios can be accommodated if each AP has 1Gb/s capacity, even though the 2Gb/s requirement cannot be accommodated in both OW DSCs simultaneously.

Capacity Aggregation

Data aggregation may be implemented across tiers via connection to both the RF and OW networks or across multiple OW connections. The aggregation may be handled at the network layer or at the physical layer where multiple OW APs act as a single multi-element cell. MTs with aggregation capabilities can dynamically associate with a subset of the available connections and adaptively determine how to distribute data traffic across the set of associated connections. This added ability increases the peak individual performance and provides more fluid traffic distribution capabilities to better account for variations in the spatial distribution of data traffic.

Adaptive CROWDs

The flexibility and dynamic capability of OW networks has been shown in recent years, and system-level research in OW networks and RF/OW HetNets is beginning to explore protocols for these dynamic adaptations. Adapting the DSC tier's physical characteristics allows for improved performance in dynamic environments, and the availability of the RFSC in a CROWD allows the OW tier to be more selective in its dynamic variations. Intelligent context-aware CROWDs will ultimately match device or environment dynamics to the appropriate tier. If the time scale of the device dynamics can be matched with the capabilities of the DSC tier, the OW DSCs can be used. When the OW link characteristics change too frequently, the RFSC can be used.

Modeling Dynamics in the CROWD

In order to demonstrate the impact that environment characteristics can have on the performance of a given technique, we develop a model for performance gain. We consider two handover techniques and compare them to a base case where the MT only uses the RF channel. The two techniques are defined below and shown in Fig. 6.

- H_1: Pure HHO case where MTs are required to use the OW tier and must establish a connection to a new OW DSC when their current connection is lost and a new signal is acquired.
- H_2: Required VHO case where MTs transfer to the RFSC upon losing an OW connection and then establish a connection to a new OW DSC when possible.

To analyze performance gain, we define C_{RF} and C_{OW} as the RF and OW capacities available to the MT, respectively. L_{HHO} and L_{VHO} are the horizontal and vertical handover latencies. We also define f_{out} as the expected frequency of OW signal loss and t_{out} as the expected time between an OW signal loss and a new OW signal becoming available. These values will vary greatly based on system layout and the MT use case. The key observation from our model is that the impact of individual parameters is tightly coupled to the value of other system parameters, thus motivating the need for detailed statistical models of these ultra-dense environments.

For example, the value of t_{out} may be similar for a stationary MT with small objects that occasionally pass through the LOS path and a rotating MT with narrow FOV, but f_{out} is likely to be much higher in the latter case. Similarly, the value of ω may be equivalent for a MT moving quickly between DSCs that are widely spread out and another MT moving slowly between DSCs that are closely located. Furthermore, the preferred technique is also tied to the relative capacities and the relative handover latencies.

In order to make the analysis tractable, we assume that signals are neither lost nor found during handover. Dwell time and other improvements are not incorporated since the model's purpose is to qualitatively demonstrate that different techniques should be preferred in different operational paradigms. The base case throughput is $R_0 = C_{RF}$. For H_1 and H_2, throughput is defined as:

$$\begin{aligned} R_1 &= C_{OW}(\text{\% of time with active OW connection}) \\ &= C_{OW}(1 - \text{\% of time without active OW connection}) \\ &= C_{OW}(1 - f_{out}(t_{out} + \text{LHHO})) \end{aligned}$$

$$\begin{aligned} R_2 &= C_{OW}(\text{\% of time with active OW connection}) + C_{RF}(\text{\% of time with active RF connection}) \\ &= C_{OW}(1 - f_{out}(t_{out} + \text{LVHO})) + C_{RF}(f_{out}(t_{out} - \text{LVHO})) \end{aligned}$$

In order to generalize parameters, we define $\alpha = f_{out}L_{HHO}$ as the percentage of time implementing HHOs in H_1 and $\beta = f_{out}L_{VHO}$ as the percentage of time implementing one-way VHOs (e.g., from RF to OW) in H_2. We also define the OW capacity gain as $\gamma = C_{OW}/C_{RF}$ and the percentage of time spent without an OW signal as $\omega = f_{out}t_{out}$. To compare performance, we define the gain between scenario i and j as $G_{ij} = R_i/R_j$ where $i, j \in \{0, 1, 2\}$ represents the pure RF, pure HHO, and required VHO scenarios, respectively.

$$G_{10} = \gamma(1-\omega-\alpha)$$

$$G_{20} = \gamma(1-\omega-\beta)+\omega-\beta$$

$$G_{12} = \frac{G_{10}}{G_{20}} = \frac{\gamma(1-\omega-\alpha)}{\gamma(1-\omega-\beta)+\omega-\beta}$$

Figure 6 observes performance gain for various γ and ω values. For $\gamma \le 1$, we know that $C_{RF} \ge C_{OW}$ and the MT is better off strictly using the RFSC; therefore, we show $\gamma = \{1.5, 2, 5\}$ representing cases where the OW capacity is 1.5, 2, and 5 times the RF capacity *available to the MT* (i.e., the difference between the RF cell's true capacity and the RF capacity in use by other by other MTs.). The depicted values of ω represent different gaps in OW DSC coverage. For example, $\omega = 0.2$ may imply outage occurring once per second for a period of 200ms or outage occurring every 5 seconds on average for an average period of 1s. The 3D images depict G_{12}. The 2D images show regions where $G_{12} \ge 1$ in yellow (i.e., H_1 outperforms H_2) and regions where $G_{12} < 1$ in blue (i.e., H_2 outperforms H_1). Regions where the rate equations are invalid (i.e., either $\beta > \omega$, $\beta > (1 - \omega)$, or $\alpha > (1 - \omega)$) are grayed out. We also gray out regions where the MT is better off strictly using the RFSC (i.e., both $G_{10} \le 1$ and $G_{20} \le 1$).

For a given CROWD configuration, the quantitative impact is dependent on system parameters (e.g., relative RF and OW capacities and handover latencies) and is time-varying for a given system due to dynamic system characteristics (e.g., capacity in use by other MTs and the MT of interest's specific use case). As such, Fig. 6 is intended to qualitatively depict the *regions* where different techniques are preferable. These results demonstrate the need for intelligent adaptation of the CROWD's network reconfiguration criteria. Furthermore, these results highlight the need for detailed statistical models of MT usage in order to obtain practical quantitative results.

First, notice that the transition line between the yellow and blue regions is dependent on γ and ω. Observing the relationship between α and β when $G_{12} = 1$, we find that this transition line has slope equal to $\gamma/(1 + \gamma)$ and an intercept at $\beta = \omega/(1 + \gamma)$. Also note that for fixed HHO and VHO latencies, the ratio of $\beta/\alpha = L_{VHO}/L_{HHO} = C$ is constant and the operating point on the line $\beta = C\alpha$ is dependent on the value of f_{out}. This line is depicted for $C = 1$, $C = 2$, and $C = 5$. The crossing point between this line and the transition line varies depending on the system parameters and outage characteristics. For larger values of C, the operating line falls in the VHO regime for a smaller range of α values.

These interconnected relationships imply the importance of understanding signal loss characteristics at the spatial resolution of CROWD networks and how these characteristics relate to different devices, applications, or use-cases, and implementing handover and network adaptation techniques that account for characteristics of different MTs (i.e., context-aware CROWDs). To the best of the authors' knowledge, there is not a significant data set and/or model that incorporates the correlation between physical usage and data demand for today's wireless devices and applications. The limited availability of such statistical models at the resolution of ultra-dense networks creates a challenge when quantitatively evaluating the validity of theoretical and simulated analysis for practical systems.

Conclusions

Spectrum availability is a critical enabler for the evolution of next generation wireless systems. The CROWD network architecture provides a novel way to exploit an alternative to the crowded RF arena, realize untapped capacity of the optical spectrum, and add supplemental wireless capacity where data demand is at its highest. The added capacity gained from CROWD networks will permit the expanded capability of mobile wireless devices, leading to enhancements in many applications supporting quality of life, energy conservation, safety, and productivity that are derived directly from ubiquitous wireless network access. Interest in the field of RF/OW HetNets continues to grow and we have described a variety of open research challenges and opportunities within this field. As we look toward future wireless networks, we believe that it is time to join the CROWD.

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