Integration of RF and VLC Systems

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Abstract
As the lighting industry moves toward long-lasting solid-state luminaires, advanced systems will begin to integrate novel use cases into the lighting infrastructure. The proliferation of wireless devices and the demand for wireless access in indoor environments create a synergy between the wireless

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R. Karlicek et al. (eds.), *Handbook of Advanced Lighting Technology*,
DOI 10.1007/978-3-319-00176-0_35

communications and indoor lighting industries. Since wireless traffic demand is at its highest in areas where artificial lighting is already in place, it makes perfect sense to incorporate novel wireless access technologies into the lighting infrastructure. This chapter focuses on the integration of visible light communication (VLC) with radio-frequency (RF) networks in order to provide additional wireless capacity in areas where RF is challenged with meeting the growing demand. We review current trends in wireless network access, provide an overview of VLC, and detail the requirements for implementation of such an integrated system.

Introduction

The introduction of solid-state lighting and the trend toward replacement of incandescent and fluorescent light sources with LED-based luminaires have been driven primarily by the promise of improved efficiency. The high-speed switching capability of solid-state lighting is another marketable trait that allows visible light communication (VLC), or the use of the visible spectrum for wireless data transfer, to be implemented with illumination-grade LEDs. This creates a potential for dual-use luminaires that provide lighting and wireless data transmission (Komine and Nakagawa 2004); (O'Brien 2011).

The mobile communication industry is in the midst of a drastic boom in data traffic and is challenged with meeting a potential 1000× growth (Qualcomm 2013). As the number of wireless devices and applications increases, the associated growth in data traffic will push the limits of current wireless network capacity. This is further impacted by a diversification of the types of wireless devices and an increase in typical application complexity. The industry accounts for approximately 1 % of the total US GDP ($146.2 billion in 2011), and estimations show that every 10 MHz of additional licensed spectrum leads to a $263 million increase in wireless application and content sales (Entner 2012); therefore. limiting the wireless capacity of end users can impede the development of novel wireless applications and stall technological advancement.

The biggest gains in aggregate wireless capacity stem from (a) increasing available spectrum and (b) increasing bandwidth density (b/s/m^2) by increasing the number of cells and decreasing the per-cell coverage area (Chandrasekhar et al. 2008). Primary motivations for VLC are that it (a) uses the vast, unused, and unregulated visible spectrum and (b) is directional, leading to small coverage area and allowing for an increased density of Access Point (AP), 2 or Base Station (BS), 2. In addition, most data traffic occurs indoors, and the lighting infrastructure is designed such that luminaires are placed according to the expected distribution of users and User Device (UD), 2. Placing APs at the luminaires adds wireless capacity where it is needed most and allows traffic to flow through the available backhaul network of the lighting infrastructure.

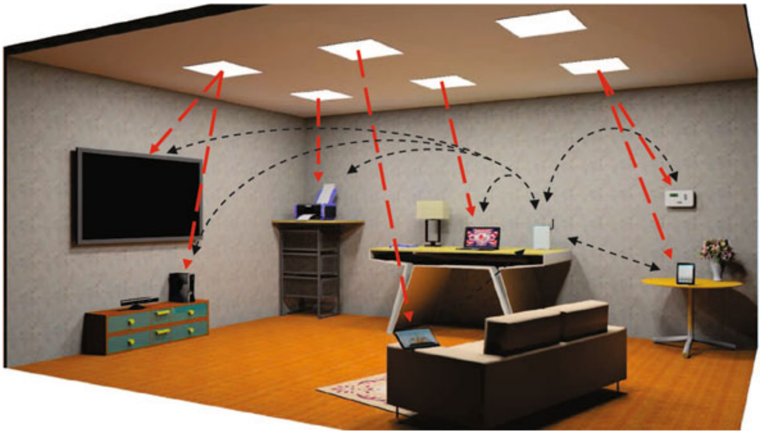

Fig. 1 Heterogeneous network integrating RF and VLC. High data rate devices are offloaded to a VLC channel in order to minimize congestion on the RF channel (*Image courtesy of Yuting Zhang)*

While VLC is a viable technology for downlink connectivity in many cases, constraints of the optical channel limit its potential as a stand-alone wireless medium. The optical channel is susceptible to blocking conditions, and a VLC uplink is not ideal since a light coming from a UD can be intrusive. In addition, RF communications currently dominate the market, and most UDs already incorporate antennas for transmitting and receiving RF signals. This motivates heterogeneous wireless networks that integrate RF and VLC as shown in Fig. 1. In an integrated system, VLC downlinks can alleviate congestion from the RF channel caused by heavily asymmetric traffic (e.g., audio/video streaming), while the RF channel provides a nonintrusive uplink and an alternative link in the event of a blocked VLC signal (Rahaim et al. 2011). Such an integration can also increase VLC market acceptance since the VLC channel is primarily supplemental, allowing UDs that are not VLC enabled to access the network as normal.

In this chapter, we provide an overview of the current trends in wireless communications, define the components of a VLC link, discuss system-level considerations for implementing a practical VLC network, and discuss the necessary features of an integrated system combining RF and VLC. We then conclude with future directions of research related to heterogeneous RF/VLC networks.

Trends in Wireless Communication

In this section, we provide a broad overview of the current trends in wireless communications. More specifically, those associated with cellular networks and wireless local area networks (WLANs). This includes trends relating to use cases, layout, and physical media, as well as the integration of various wireless networks.

WLANs and Cellular Networks

The most widespread wireless networks today are WLANs and cellular networks. The majority of WLANs are based on the IEEE 802.11 standard or Wi-Fi. Both Wi-Fi WLANs and cellular networks implement RF communications; however, there are differences that primarily stem from their original use. WLANs operate at a range on the order of 100 ft and are intended to provide high data rate connections to UDs in the home or work place. The range of a macrocell cellular BS is measured in miles and was originally intended for voice traffic to mobile UDs indoors or outdoors. Since voice traffic is now digitized and many mobile devices now accommodate data traffic, cellular networks have started deploying smaller cells (e.g., microcells, femtocells, etc.), and many UDs are capable of accessing various wireless networks.

Regarding the RF spectrum, Wi-Fi WLANs use various ISM bands with unlicensed spectrum, whereas cellular networks use licensed spectrum owned by the service provider. This implies that Wi-Fi contends with other devices and protocols using the spectrum, whereas cellular networks can allocate dedicated resources to specific UDs. Wi-Fi WLANs implement contention-based multiple access, specifically carrier sense multiple access (CSMA), whereas cellular networks implement resource allocation methods, such as frequency-division or code-division multiple access (FDMA, CDMA).

Asymmetric Traffic Distribution

IP data traffic has evolved from early dominance of asymmetric web surfing applications, to relatively symmetric peer-to-peer networking, to the current dominance of highly asymmetric applications such as IP TV, online gaming, and streaming music. The asymmetry in these applications leads to a need for added capacity in the wireless downlink. In cellular networks, supplemental downlink has been enabled in recent releases of the LTE Advanced standard. This combines unpaired spectrum with the primary paired spectrum in order to provide additional capacity from BS to UD. The idea of adding downlink capacity via an alternative medium can also be applied to WLANs; however, the implementation will vary for networks where contention-based multiple access methods are used rather than resource allocation methods.

Small Cells

Over the past 50^+ years, the majority of wireless capacity gains have come by means of increased cell density and reduced transmit distance, in turn, providing similar aggregate coverage while reducing per-cell coverage area. As cells become smaller and cell density increases, wireless network capacity improves due to spatial reuse and increased area spectral efficiency (b/s/Hz/m^2) (Nakamura et al. 2013).

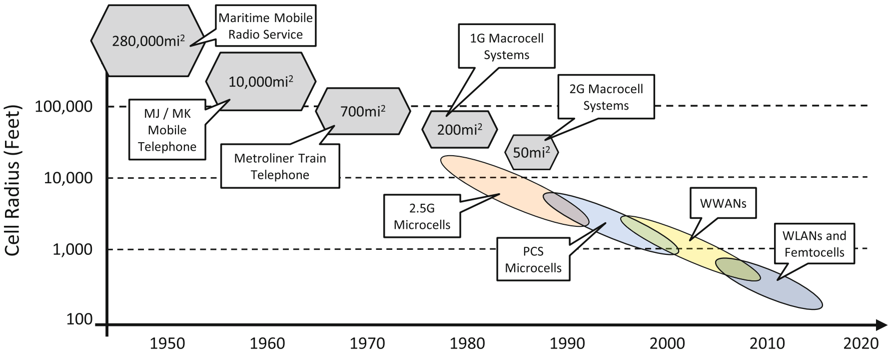

Fig. 2 Historical trend of cell coverage (*Image modified from* (ZTE Corporation 2012))

Figure 2 depicts the small cell trend leading to WLANs and femtocells (small, low-power, in-home cellular BSs that connect to a service provider's network through an IP network). Although Wi-Fi WLANs are not part of the cellular network, they are often considered small cells.

Macrocells and femtocells are both *controlled* by a global entity (i.e., service provider); however, femtocell BSs are *owned* by a local entity (e.g., home owner), similar to WLAN APs. Femtocell BSs and WLAN APs are therefore placed in an ad hoc manner as opposed to the planned layout of macrocell BSs. This ad hoc layout can affect the quality of service (QoS) of UDs in the network because of interference between neighboring WLANS or femtocells operating in the same band (Fig. 3a, b). Femtocell BSs and UDs also interfere with overshadowing macrocells and UDs assigned to the macrocell (Fig. 3c, d). The converse is also true (Fig. 3e, f). This interference is compounded by the ad hoc placement of small cell APs or BSs as opposed to the structured layout of larger cells in cellular networks. As the number of small cells continues to grow, there is interest in a paradigm shift from the typical macrocell coverage model to an "Inside-Out" model where small cells cover the indoor space and also provide access to UDs in the vicinity outdoors. The problem that arises in current small cell implementations is that typical femtocell owners prefer to utilize closed access in order to provide the best coverage to their UDs rather than open access which has been shown to provide better aggregate network performance (Andrews et al. 2012).

Directional Wireless

Continuing the small cell trend beyond a single AP or BS per home raises questions regarding the appropriate infrastructure. The omnidirectional emission pattern of most WLAN APs and femtocell BSs limits the minimum effective coverage area since reducing cell size is associated with reducing the maximum distance between the AP or BS and a UD. Directional wireless media, such as VLC, infrared (IR), and mm-wave communications, can emit a narrow signal beam – providing a small

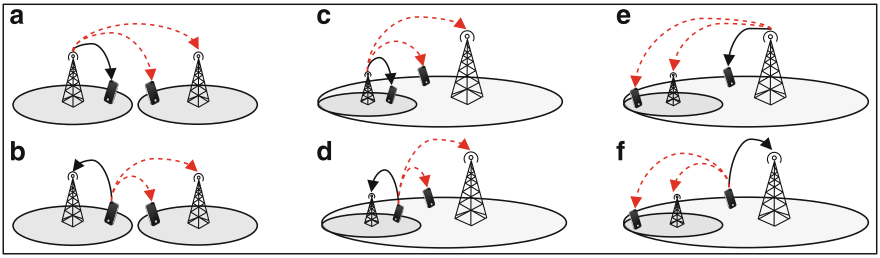

Fig. 3 Interference in small cell networks. *Solid lines* indicate signal and *dashed lines* indicate interference. Interference occurs between small cells (**a**, **b**) and between tiers using similar resources (**c**–**f**)

coverage area at the working surface without the same distance requirement. In this case, emission pattern and transmit power jointly affect the coverage area.

The IEEE 802.11 ad standard (IEEE 2012) offers multi-gigabit throughput in the 60 GHz mm-wave ISM band. The standard defines four channels, each with 2.16 GHz channel bandwidth as opposed to the maximum 160 MHz channel bandwidth defined in the IEEE 802.11 ac standard which operates in the 5 GHz ISM band. Higher bandwidth promises higher potential throughput, and the directionality of the medium allows the signal to be dynamically steered or directed toward the UD; however, higher-frequency signals suffer from very high attenuation or complete blocking when physical barriers obstruct the line-of-sight (LOS) path.

Heterogeneous Wireless Networks

Various wireless networks have been designed to operate optimally under specific conditions; however, many of today's UDs are not designed for a specific purpose. This is leading the wireless communication industry toward mobile convergence where wireless networks of different sizes and access technologies work together in a heterogeneous network (HetNet) (Andrews 2013). Consider that a smart phone can be used for voice traffic while riding in your car, web surfing while walking around your home, and video streaming while sitting on your couch. Each of these instances has an increasing amount of traffic and a decreasing requirement for mobility; therefore it would make sense for your phone to transfer between a macrocell in the cellular network, a femtocell or WLAN, and a highly localized directional channel such as VLC or 60 GHz.

The objective of HetNets and mobile converged networks is to incorporate a framework that intelligently distributes UDs among the various cells or networks in order to opportunistically exploit characteristics of the channel that best fits the current mode of operation. This distribution can be across tiers in a multi-tier HetNet where spectrally similar APs or BSs are distinguished by density and transmit power or across heterogeneous access technologies (e.g., Wi-Fi offloading from cellular networks). Figure 4 and the smartphone example both observe a distribution of

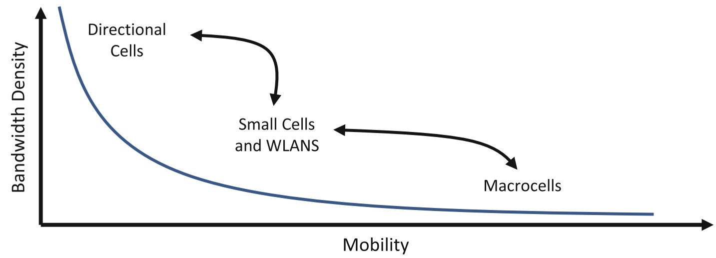

Fig. 4 UDs should be opportunistically distributed across various networks

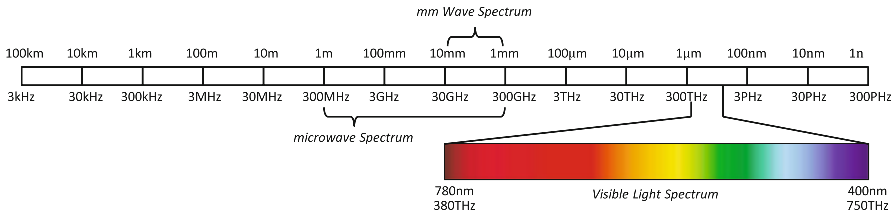

Fig. 5 Electromagnetic spectrum

UDs based on mobility and rate requirements; however, other traits can be incorporated in the decision process.

Visible Light Communication (VLC)

VLC is an optical wireless communication (OWC) technique that utilizes the visible spectrum for data transmission (Elgala et al. 2011). VLC implements intensity modulation with direct detection (IM/DD), implying that the optical intensity is modulated by the desired signal which is recovered via direct conversion of the optical signal to an electrical current. Although the visible light spectrum, shown in Fig. 5, offers a vast range from 400 to 780THz, the use of IM/DD limits the single channel bandwidth to the switching speed of the LED. The immense spectrum can be exploited though wavelength division multiplexing (WDM) techniques that allow many parallel channels to be transmitted using various frequency bands in the optical range. Multi-gigabit per second VLC has been demonstrated with WDM using three colors (red, green, and blue), and there is potential for much higher parallelism given narrowband emitters and receivers (Kottke et al. 2012).

Channel Model

In an IM/DD OW channel, $X(t)$ is defined as the instantaneous optical *signal* power, or intensity [W], of the light source; therefore min $(X(t)) = 0$ and the constraint

$X(t) \geq 0$ holds for all t. The transmitter generates an average signal power, P_t, and an optical receiver produces an instantaneous received signal current, $y(t)$, such that

$$P_t = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} X(t)dt \tag{1}$$

$$y(t) = R(X(t) * h(t)) + n(t) \tag{2}$$

where $h(t)$ is the channel response, R is the responsivity of the photosensor [A/W], and $n(t)$ is the electrical noise (Kahn and Barry 1997).

Given the presence of a LOS path, the approximation $h(t) = V H\delta(t - \tau)$ is typically very good. The visibility of the link, V, is 1 when the LOS path is unobstructed and 0 otherwise. The propagation delay, τ, represents the time difference between the transmitted and received signal, and the LOS DC channel gain, H, is dependent on both the angle of emission, ϕ, and the angle of arrival, υ. For a VLC receiver with concentrator optics, H is defined as

$$H = \begin{cases} \frac{A}{d^2} R_o(\phi) T_s(\upsilon) g(\upsilon) \cos(\upsilon) & 0 \leq \upsilon \leq \Psi_c \\ 0, & \upsilon \geq \Psi_c \end{cases} \tag{3}$$

where A is the area of the photodiode, d is the distance between transmitter and receiver, Ψ_c is the concentrator FOV, and $R_o(\phi)$, $T_s(\upsilon)$, and $g(\upsilon)$ are the angle-dependent radiation pattern, filter transmission, and concentrator gain, respectively. The average received signal current, $\bar{y}$, is proportional to the average transmitted optical signal power such that $\bar{y} = RHP_t$.

Note that OWC requirements, such as illumination in dual-use VLC luminaires, place a constraint on the average transmitted optical power as opposed to the constraint on average electrical transmit power in RF communications. In order to compare performance of various modulation techniques under similar optical power constraints, the OWC signal to noise ratio is defined relative to P_t,

$$SNR = \frac{(RHP_t)^2}{\sigma^2} \tag{4}$$

where σ^2 is the total noise variance in the electrical domain. Error rate equations for modulation techniques also differ from convention when analyzed with this value of SNR. Since illumination requirements can vary in scenarios where dimming or color-tunable luminaires offer dynamic lighting environments, the SNR and achievable data rate will also vary with the lighting (Gancarz et al. 2013).

System-Level Constraints

Given the potential for VLC as a high data rate point-to-point wireless access technology, the next step in the development of a practical VLC implementation is to determine the potential use cases within an environment incorporating mobile

UDs and dynamic signal conditions. In order to meet the demands of most UDs, the wireless link should be bidirectional and promise a high probability of connectivity.

In a dual-use scenario, the optical power emitted in the downlink direction achieves both lighting and communication requirements; however visible light generated from a UD does not assist in meeting room lighting requirements and is likely to be considered intrusive to the user. Because of this, VLC links between a dual-use luminaire and a UD are typically proposed as an asymmetric link implementing an infrared (IR) or RF uplink (O'Brien et al. 2008). In order to maximize coverage in a wireless network, AP layout should be configured with appropriate overlap so that a UD moving through the environment maintains connectivity between cells and doesn't lose network connectivity as it moves out of range of an AP. In addition to out-of-range signal loss, VLC suffers from signal loss due to blocking conditions where the LOS path is obstructed. In the next section, we discuss how heterogeneous network integration can mitigate the effect of these constraints.

System Integration

Integration of VLC in the higher layers of a wireless communication network provides a directional medium that can be opportunistically utilized for high data rate traffic to UDs operating in a low-mobility condition. This adds localized downlink channels, allowing intelligent networks to distribute UDs across the curve in Fig. 4. It also allows the network layout to be planned without a requirement of overlapping VLC cells since the regions between cells are covered by the overshadowing RF channel. In addition, VLC-enabled UDs are capable of (a) using the nonintrusive RF uplink for handshaking and bidirectional traffic and (b) switching to a symmetric RF link in cases where the VLC signal is lost. While RF wireless networks would benefit from the additional capacity of supplemental VLC downlinks, the following considerations must be accounted for when developing and optimizing such integrated systems.

System Layout

The structure of wireless networks is in the process of moving from planned macrocells, maintained by a global entity, to a high-density ad hoc placement of small cells, each maintained by a local entity. Since these small cells don't have any centralized organization, they typically provide some level of self-organizing capability. This is required because the emission pattern of a WLAN or femtocell is typically wide enough to generate interference in an area operated by an unassociated entity (e.g., neighboring apartments each with a Wi-Fi WLAN set to the same channel). On the other hand, VLC cells have a relatively contained emission pattern and can be planned locally because intercell interference will be negligible outside of the area responsible to the local entity. The lighting

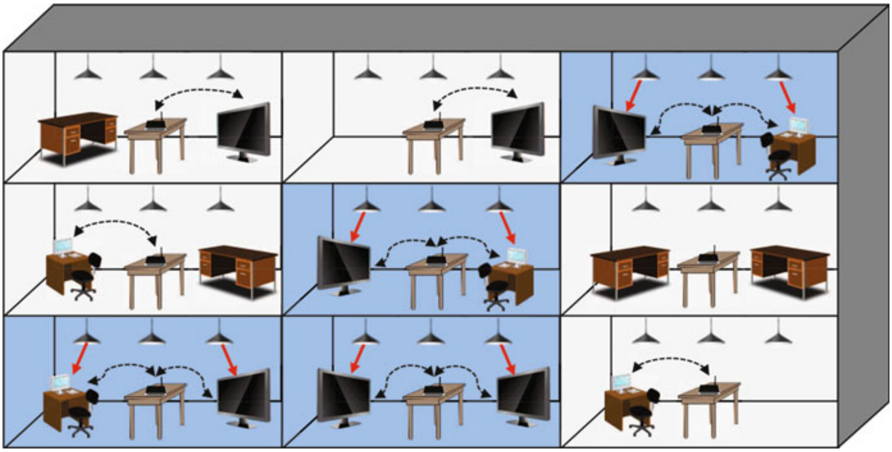

Fig. 6 Apartment complex with various entities. All apartments have interfering RF small cells, and the blue apartments utilize VLC APs to offload wireless traffic from the RF channel

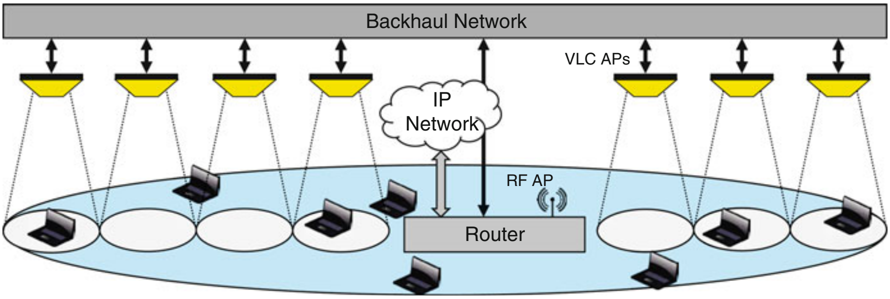

Fig. 7 Basic service set for an RF small cell with VLC integration

infrastructure provides a locally planned distribution of luminaires that maps well to the distribution of UDs in many environments.

Figure 6 shows a hypothetical environment where VLC cells supplement RF small cells within an extended service set encompassing many other small cells. When traffic is offloaded to a VLC AP, it removes congestion from the associated small cell and interference from neighboring cells. The basic service set for the integrated system, shown in Fig. 7, consists of multiple UDs, one or more VLC APs, and a single central AP consisting of an RF AP, a router, and a gateway to external networks. All UDs are equipped with RF transceivers in order to maintain backward compatibility on the RF channel, and VLC-enabled UDs are also equipped with a VLC receiver. Connections to the public network pass through the gateway at the central AP, and the backhaul network connects VLC APs and the central AP.

For a given UD associated with a VLC AP within the coverage area of the RF small cell, the physical links available can be implemented in the three

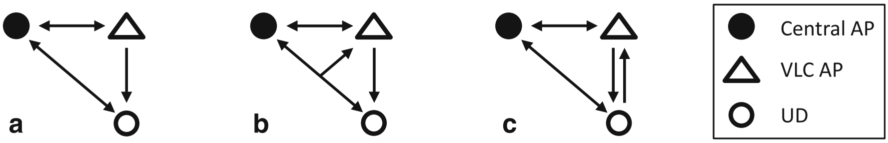

Fig. 8 Potential connections for a UD in an integrated system

configurations shown in Fig. 8. Figure 8a depicts the basic system with a VLC downlink and bidirectional link to the RF AP. Figure 8b assumes the VLC AP has an RF transceiver such that the UD has an additional bidirectional link to the VLC AP; however this channel is in contention with the central AP and other UDs or VLC APs using the same shared RF channel. Figure 8c assumes the UD is enabled with an additional transmitter and the VLC AP has a corresponding receiver such that a non-interfering uplink channel (e.g., IR) is available. In case (a), traffic between the UD and external networks can either flow from UD to central AP, central AP to UD, or central AP to VLC AP to UD. In the scenarios where an uplink from UD to VLC AP is available, there is the additional path from UD to VLC AP to central AP. Within the local network, traffic may also flow from UD to central AP to VLC AP.

Backhaul Network

In order to observe the desired spatial reuse of the optical channel, VLC APs should be spatially distributed throughout the environment. Each of these VLC APs requires network connectivity in order to relay network data to associated UDs; therefore data packets must be able to pass between the central AP and each of the VLC APs. The backhaul network allows data traffic and additional overhead to flow. There are various options for implementing the backhaul network in regard to both the physical channel and the network topology connecting the central AP and the set of VLC APs.

Physical Channel

In networking, a layer model is commonly used to separate the various components of a communication system. The physical channel is typically the fundamental layer that consists of the basic hardware transmission technologies. As the lighting industry moves toward intelligent systems capable of dynamically adapting to user preferences, a key component in the design is the physical channel providing connectivity between devices. Currently, controllable luminaires are often connected with copper wire (e.g., DALI, DMX) or RF mesh networks (e.g., Zigbee) (IES TM-23-11 2011). These techniques provide low data rate throughput – on the order of 100 kbps – which is appropriate for control; however, they are not intended for high data rate traffic. Two technologies that provide promise for high throughput are power line communication (PLC) and Ethernet – specifically power over Ethernet (PoE). PLC and PoE provide both communication and power, minimizing installation overhead. In home PLC is capable of operating on the order of 100 Mbps, and PoE can be utilized with gigabit Ethernet links. The IEEE PoE+ standard provides up to 25.5 W of power, and some vendors provide PoE+ products offering up to 51 W of power.

Network Topology

A network's topology describes how the various components of the network are connected. The networks *physical topology* defines how the components are physically connected, whereas the *logical topology* defines how traffic can flow in the network. Figure 9 depicts some of the potential topologies to be considered when defining the backhaul network. A *star* topology consists of a central hub that connects to each of the other nodes in the network. In the case of the backhaul network, the central AP would connect to each VLC AP with a unique link. The *tree* topology observes a hierarchy of nodes, beginning with a root node. The root node connects to one or more other nodes with unique links. Each of these nodes may connect to additional nodes that are not already part of the network. The *line* topology is a specific type of tree where each node only has a single child node. In the backhaul network, the central AP is the root node and each VLC AP may route traffic to additional nodes. The *mesh* topology can have a link between any pair of nodes, as long as a path exists between any two nodes in the network. Each node acts as an independent router, allowing nodes to connect to each other in various multi-hop paths. The *bus* topology connects all nodes to a single shared channel. This allows all nodes to have a direct link with any other node; however they must contend for use of the channel.

If the channel used for backhaul connectivity is shared between multiple VLC APs, as in the bus topology, it can become a system bottleneck. This is also the case when a link is the only path connecting the central AP to a subset of VLC APs, as in the tree topology, since all traffic to the subset will need to be routed through the link. The system does not need to operate under the requirement that all VLC APs are

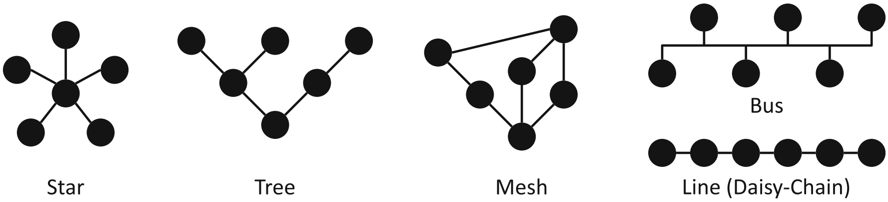

Fig. 9 Some of the various potential network topologies

capable of operating at full capacity simultaneously. For example, assume a system where VLC APs are either unused or at max capacity of X b/s with $P(\max) = 0.5$. If four VLC APs are connected by a bus with capacity $3X$ b/s, the backhaul is a bottleneck when all VLC APs have an associated UD. Since this occurs $100(P(\max))^4 = 6.25$ % of the time, requirements are satisfied 93.75 % of the time. If $P(\max) = 0.2$, the backhaul satisfies requirements 99.84 % of the time. Beyond a certain point, additional backhaul capacity provides diminishing gains in the probability of being overloaded.

Handshaking

Handshaking is the process of negotiation between two nodes that allows both to determine that the transmitted data was received. This can occur between the source and destination nodes as well as between two nodes that share a link. When a UD is receiving packets from a VLC AP, an acknowledgment (ACK) should be sent to the VLC AP in order to provide reliability of packet delivery at the physical layer. Given the available paths between a UD and the VLC AP, an ACK can either be sent directly to the AP in case (b) and (c) from Fig. 8 or routed through the central AP in case (a). Since the addition of VLC should allow the RF and VLC media to operate simultaneously, the uplink channel is not reserved, and the ACK may take an indefinite time to reach the VLC AP. This implies that the VLC AP should not wait for the ACK before sending the next packet. One potential handshaking method is a negative acknowledgment (NAK) protocol. In a NAK protocol, the VLC AP would maintain a recent history of previous packets and place a sequential label on each packet sent to the UD. Rather than sending an ACK for every packet, the UD would instead reply with a NAK when it notices a packet error or a missing packet in the sequence. When the VLC AP receives a NAK for a specified packet, it retransmits the packet if it is still in the packet history. Some higher-layer streaming protocols also allow for lost packets, in which case a VLC channel without any physical layer acknowledgments is acceptable since packets with errors can be disregarded.

Traffic Distribution

In an environment with many UDs and multiple VLC APs, the system should be able to intelligently determine how to distribute the UDs across the various APs. In a static environment, the simplest form of distribution is to offload a UD to a localized VLC channel whenever one is available; however having multiple UDs associated with a single VLC AP can potentially saturate the VLC channel. In addition, for certain backhaul topologies, it is possible that a link in the backhaul network is saturated. In either case, associating some of the VLC-enabled UDs with an underutilized RF channel will allow the network to operate with better performance.

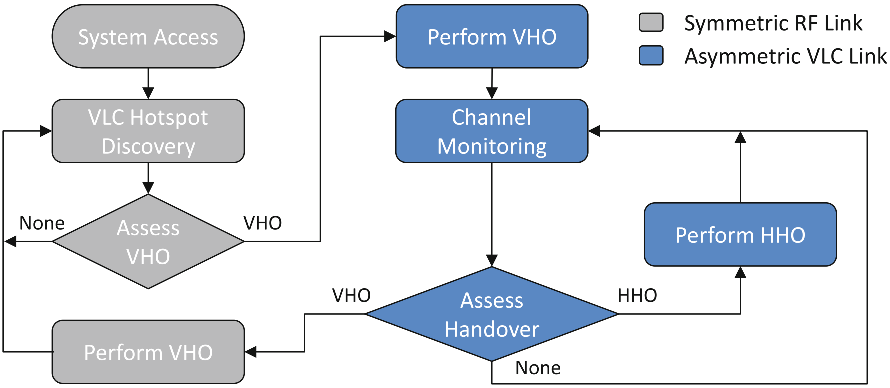

Fig. 10 High-level handover flow diagram

For a specific instant in time within a dynamic environment, highly mobile UDs or UDs with a high probability of VLC signal loss are better suited for the overshadowing RF channel. The highly localized signal of a VLC channel is best suited for quasi-static UDS – devices that are mobile in nature but typically used in a stationary manner. This includes devices like laptops or tablets that are seldom used in motion. Since switching between channels requires overhead, the network may perform better when a highly mobile UD is associated with the RF channel rather than the VLC AP.

Handover

In a dynamic environment, traffic flow must be rerouted when a signal is lost or an AP becomes overloaded. The process of rerouting traffic to a different AP is called handover (Pollini 1996; Nasser et al. 2006). When switching between two APs of the same type, as in transferring from one VLC AP to another, a *horizontal handover* (HHO) occurs. When switching between APs of different types, as in a transfer from Wi-Fi to VLC, a *vertical handover* (VHO) occurs. Figure 10 shows a high-level flow diagram of a single UD's actions in an integrated system incorporating a single RF link and multiple asymmetric VLC links. The UD first accesses the network via the RF channel. Downlink traffic is rerouted through the appropriate VLC AP if the UD discovers one to be available and the assessment determines that the handover should be initiated.

In the process of making a handover decision, the UD must first determine whether any VLC APs are available. The UD observes the VLC channel while VLC APs send an intermittent beacon with a unique identifier. If a VLC AP is found and determined to be accessible, handover can be initiated. The assessment of whether the specific UD should perform a handover can either be done (a) in a distributed *user-controlled* manner where each UD makes a decision specifically on the knowledge of the available channels; (b) in a centralized *network-controlled* manner where the intelligent network maintains knowledge of the UDs within the network and their potential AP associations, then accordingly distributes the UDs such that they are well divided among APs; or (c) in a *mobile-assisted* manner where UDs relay knowledge of their current status (e.g., traffic pattern, mobility pattern, etc.) to the centralized network coordinator such that traffic is distributed among APs in a more optimal way.

A handover request can either be *optional* or *mandatory*. When the RF channel is in use and a VLC AP is located, the VHO is optional since a UD can remain on the RF channel. When a UD is using a VLC link and the signal is lost, VHO is mandatory since the VLC downlink no longer exists. When multiple channels are available, the assessment process should determine if it's better to remain on the current link or initiate a handover. A utility function evaluates parameter values of the various channels, and a handover is initiated when the utility of the new channel meets the requirements for handover. Immediately switching to the highest utility can lead to the ping-pong effect where multiple handovers occur while transitioning between channels; therefore the requirements can include an absolute threshold that the utility of the current channel must drop below or a hysteresis margin, h, such that the utility of a new channel must be greater than the utility of the current channel plus h.

In the case of user-controlled assessment, UD-centric parameters such as channel reliability, signal strength, or required UD power consumption are used. For network-controlled assessment, network-centric parameters such as channel usage are used. With mobile-assisted assessment, a combination of both parameter sets is used. The utility function observes a desired set of parameters for the network, p_1 through p_n, and a set of weights for the network or the specific UD, ω_{p_1} through ω_{p_n}:

$$U = f\left(\omega_{p_1}, p_1, \omega_{p_2}, p_2, \ldots, \omega_{p_n}, p_n\right) \tag{5}$$

Given the two signal loss conditions for an OWC channel, the type of VHO may differ. An *immediate* handover occurs as soon as the primary signal is lost, whereas a *delayed* handover dwells for a specified time to see if the channel returns before initiating the handover. If an out-of-range signal loss occurs, the signal is usually lost for an extended period – implying that the handover should be made immediately. When a blocking condition occurs, it's likely that something is passing through the LOS path and will return soon – implying that the device should delay before handover initiation in the likelihood that the signal will return (Hou and O'Brien 2006).

As an example, consider a system with an R_V b/s VLC link, R_W b/s Wi-Fi link, X second handover delay, and Y second VLC outage time. After T seconds,

$$D = R_V(T - Y) \tag{6}$$

$$I = R_W(Y - X) + R_V(T - Y - X) \tag{7}$$

where D is the throughput of a UD that waited for the VLC to return and I is the throughput of a UD that immediately switched to the Wi-Fi link when the VLC signal was lost and switched back when it returned. Comparing these two values,

$$I - D = R_W Y - (R_V + R_W)X \tag{8}$$

we find that immediate handover performs better when $Y > \frac{R_V + R_W}{R_W} X$ and delayed handover is optimal when $Y < \frac{R_V + R_W}{R_W} X$. Since the system doesn't know a priori when the VLC link will return, predictive techniques can observe past tendencies, UD motion or rate of signal loss in order to increase the probability that an appropriate decision is made (Rahaim et al. 2012).

Once the network or UD determines that a handover should be initiated, both ends need to coordinate the handover. In a simple case, this implies that the router updates where incoming traffic is routed and the UD changes its expectation of where the downlink traffic is coming from. If a UD is switching to resource allocation channel that is in use by multiple UDs, this coordination includes the definition of the allocated resources for the UD. For example, if a UD is joining a VLC AP using orthogonal frequency-division multiple access, the UD must know which frequency bins to observe.

Conclusions

In summary, integration of VLC luminaires with an RF network provides much needed capacity to keep up with the requirements for the next generation of wireless devices. The initial planning of the system requires an appropriate layout with enough backhaul capacity to satisfy the wireless requirements with high probability. Traffic routing for a given UD should be determined by weighting the additional costs of hardware with the routing complexities for simplified systems. When a system has multiple UDs, distribution of traffic should be such that any individual channel has a low probability of being overloaded. In a dynamic system, appropriate decisions should be made in real time such that the distribution remains satisfactory as network conditions change.

Future Directions

Moving forward, there are many directions for the future of research in heterogeneous VLC and RF networks. The use of multiple-input-multiple-output (MIMO) VLC is an area drawing a great deal of attention due to the parallelism leading to increased link capacity (Butala et al. 2013). From the integrated system view, MIMO VLC fits into all of the concepts described in the chapter since a VLC "cell" can incorporate a set of VLC luminaires. In addition, MIMO allows for dynamic cells since UDs can select the set of luminaires to associate with. This adds some complexity to the traffic distribution and handover decisions, but provides additional flexibility for the system.

The RF uplink and network connectivity also adds potential for dynamic rate adaptation and lighting control. As UDs move around the environment, the quality of the VLC channel will vary. If the UD can send feedback directly to the VLC AP, the system can incorporate a control loop for illumination and modulation. Dynamic rate adaptation occurs when a UD observes a change in the signal quality and accordingly requests an increase or decrease in the modulation scheme or modulation order.

Another area of potential research is in the scope of large-scale networks and small cell implementation. Given that adding UDs to small cells generates additional traffic and can degrade performance of other UDs, many small cell owners are resistant to the idea of open access. However, given localized VLC channels that are contained within the premises of the local entity and provide the required capacity for UDs belonging to the small cell owner, it is possible that owners would be more willing to open access to the RF channel for secondary UDs.

Finally, integration of VLC luminaires into traditional RF networks creates a wireless link between the lighting infrastructure and devices in the environment. The directionality of the VLC channel provides localization capabilities and additional information that can improve the systems knowledge of light field. Such integration can improve lighting functionality while also allowing the lighting industry to tap into the wireless broadband market and provide additional wireless capacity to meet the growing demand for ubiquitous high-speed wireless network connectivity.

References

Andrews J (2013) Seven ways that hetnets are a cellular paradigm shift. IEEE Commun Mag 51 (3):136–144. doi:10.1109/MCOM.2013.6476878

Andrews J, Claussen H, Dohler M, Rangan S, Reed M (2012) Femtocells: past, present, and future. IEEE J Sel Areas Commun 30(3):497–508. doi:10.1109/JSAC.2012.120401

Butala P, Elgala H, Little T (2013) SVD-VLC: a novel capacity maximizing VLC mimo system architecture under illumination constraints. In: GLOBECOM workshops (GC Wkshps), 2013 IEEE, http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6825137

Chandrasekhar V, Andrews J, Gatherer A (2008) Femtocell networks: a survey. IEEE Commun Mag 46(9):59–67. doi:10.1109/MCOM.2008.4623708

Elgala H, Mesleh R, Haas H (2011) Indoor optical wireless communication: potential and state-of-the-art. IEEE Commun Mag 49(9):56–62. doi:10.1109/MCOM.2011.6011734

Entner R (2012) The wireless industry: the essential engine of us economic growth. Technical report, Recon analytics. http://reconanalytics.com/2012/04/essential-engine-of-us-economic-growth/

Gancarz J, Elgala H, Little T (2013) Impact of lighting requirements on VLC systems. IEEE Commun Mag 51(12):34–41. doi:10.1109/MCOM.2013.6685755

Hou J, O'Brien D (2006) Vertical handover-decision-making algorithm using fuzzy logic for the integrated Radio-and-OW system. IEEE Trans Wirel Commun 5(1):176–185. doi:10.1109/TWC.2006.1576541

IEEE (2012) IEEE std 802.11ad-2012 (amendment to IEEE std 802.11-2012, as amended by IEEE std 802.11ae-2012 and IEEE std 802.11aa-2012)

IES TM-23-11 (2011) Lighting control protocols. Technical report. Illuminating Engineering Society

Kahn J, Barry J (1997) Wireless infrared communications. Proc IEEE 85(2):265–298. doi:10.1109/5.554222

Komine T, Nakagawa M (2004) Fundamental analysis for visible-light communication system using LED lights. IEEE Trans Consum Electron 50(1):100–107. doi:10.1109/TCE.2004.1277847, http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4654267&tag=1

Kottke C, Hilt J, Habel K, Vučić J, Langer KD (2012) 1.25 gbit/s visible light wdm link based on dmt modulation of a single rgb led luminary. In: European conference and exhibition on optical communication, Optical Society of America, p We.3.B.4, doi:10.1364/ECEOC.2012.We.3.B.4, http://www.opticsinfobase.org/abstract.cfm?URI=ECEOC-2012-We.3.B.4

Nakamura T, Nagata S, Benjebbour A, Kishiyama Y, Hai T, Xiaodong S, Ning Y, Nan L (2013) Trends in small cell enhancements in lte advanced. IEEE Commun Mag 51(2):98–105. doi:10.1109/MCOM.2013.6461192

Nasser N, Hasswa A, Hassanein H (2006) Handoffs in fourth generation heterogeneous networks. IEEE Commun Mag 44(10):96–103. doi:10.1109/MCOM.2006.1710420

O'Brien D (2011) Visible light communications: challenges and potential. In: Photonics conference (PHO), 2011 IEEE, pp 365–366. doi:10.1109/PHO.2011.6110579

O'Brien D, Zeng L, Le-Minh H, Faulkner G, Walewski J, Randel S (2008) Visible light communications: challenges and possibilities. In: Personal, indoor and mobile radio communications, 2008. PIMRC 2008. IEEE 19th international symposium on, pp 1–5. doi:10.1109/PIMRC.2008.4699964

Pollini G (1996) Trends in handover design. IEEE Commun Mag 34(3):82–90

Qualcomm (2013) The 1000x data challenge. http://www.qualcomm.com/solutions/wireless-networks/technologies/1000x-data, [Online]. Accessed 6 Mar 2014

Rahaim M, Vegni A, Little TDC (2011) A hybrid radio frequency and broadcast visible light communication system. In: GLOBECOM workshops (GC Wkshps), 2011 IEEE, pp 792–796. doi:10.1109/GLOCOMW.2011.6162563

Rahaim M, Prince G, Little T (2012) State estimation and motion tracking for spatially diverse VLC networks. In: Globecom workshops (GC Wkshps), 2012 IEEE, pp 1249–1253. doi:10.1109/GLOCOMW.2012.6477760

ZTE Corporation (2012) Evolution of microwave radio for modern communication networks. http://wwwen.zte.com.cn/endata/magazine/ztetechnologies/2012/no5/articles/201209/t20120912_343888.html, [Online]. Accessed 24 Mar 2014