An Ultra-Dense IoT Architecture using Hybrid CSMA with Sector Based Scheduling (CSMA/SS) via Visible Light Communications

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Abstract

Future dense networks will be expected to reconcile the coexistence of high-rate mobile traffic mixed with low-rate and potentially delay-sensitive Internet of Things (IoT) traffic. The conflicting requirements for each traffic type challenge the efficient use of the available spectrum and suggest a need for new access technologies. We propose a novel approach in which sectors of a dense network can be engaged using out-of-band signaling employing the visible spectrum. This function serves the purpose of mitigating congestion by specifying which sectors are active and decreasing the number of devices contending for RF resources at any given time. We show how this solution can improve utilization of the RF channel in the presence of heavy contention while removing the need for centralized knowledge of devices in the network.

Categories and Subject Descriptors

C.2 [**Comm Networks**]: Architecture and Design

General Terms

CSMA with Sector Based Scheduling (CSMA/SS)

Keywords

Visible Light Communication, Ultra-Dense Networks

1 Introduction

Internet-of-Things (IoT) devices will be a significant contributor to the increasing wireless network demand. In the next generation of wireless communication systems, or 5G, the ultra-dense deployment of IoT devices will add an increasing amount of RF congestion. New wireless access techniques are required to maximize use of the available RF bandwidth and increase aggregate throughput in these environments. IoT devices must also be energy efficient and the wireless connection must provide security and privacy.

The lighting infrastructure is well suited for deployment of dense wireless access points (APs) and luminaires can be used to modulate coded light via visible light communications (VLC). There is a growing market for coded light due to broad interest in visible light positioning (VLP) and lighting companies are exploring the addition of low data rate VLC capabilities for this purpose [1]. Researchers have shown the potential of solar-cells operating in a dual-use paradigm for energy harvesting and as low data rate VLC receivers [5]. Heterogeneous integration of broadcast VLC luminaries has been shown to add supplemental capacity to RF small cell networks [4]; however, VLC data rates from VLP transmitters and solar-cell receivers are on the order of 100kb/s and not comparable with future WiFi WLAN rates.

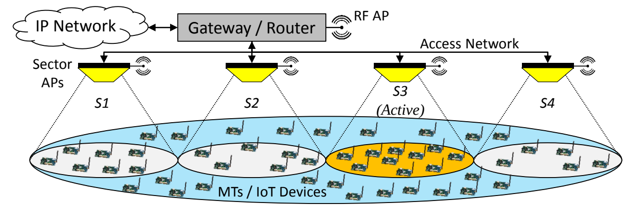

Figure 1. System architecture with four sectors.

In this paper, we describe how low data rate VLC can benefit IoT energy use and security while also improving utilization of the RF resources. The later is done with a sector selection process using VLC for out-of-band signaling while also energizing IoT devices that utilize the incident light for energy harvesting. Section 2 introduces the proposed architecture. Section 3 describes the energy, security, and communications benefits. Section 4 concludes the paper.

2 Proposed Architecture and Protocol

The proposed architecture (Figure 1) consists of a gateway, router, central RF AP, and an access network connecting one or more Sector APs (SAPs). The SAPs each have a wired connection to the access network, a VLC transmitter, and an interface to the RF network. IoT devices and other mobile terminals (MTs) are assumed to have an RF interface. MTs with a VLC receiver are considered sectored MTs while those without VLC access are non-sectored MTs.

When accessing the network, MTs can connect to the central RF AP or to any of the SAPs via the RF interface. The RF medium is assumed to be shared with a carrier sense multiple access (CSMA) scheme that allows for distributed coordination. Backwards compatibility is maintained for devices without a VLC receiver and for VLC-enabled devices without a reliable VLC signal (e.g., devices out of range of a

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VLC sector or in the case of an occlusion since VLC is susceptible to blocking). When sectored MTs utilize the system, they also monitor the VLC signal for information about their sector and only use the RF interface if their sector is active.

The highly localized VLC signal provides a sector key that adds an extra degree of security to data transmitted on the RF channel [2]. It also indicates if the sector is active and allows MTs to implement our proposed hybrid CSMA with sector based scheduling (CSMA/SS). The protocol reduces instantaneous demand by only allowing sectored MTs to utilize the RF interface when their sector is active. This scheduling increases utilization when the RF channel is congested. CSMA/SS is similar to hybrid CSMA/TDMA [3]; however there is no need for centralized coordination or scheduling of time slots for specific MTs since the time allocation is based on the location and distribution of MTs.

3 System Benefits

The proposed system has the potential to improve energy efficiency, security, and throughput – essential areas for deployment of wireless networks with densely distributed and self sustainable IoT devices. The energy benefits are in terms of energy consumption requirements and the ability to harvest energy from the environment. IoT devices using solar cells as VLC receivers benefit from dual use of the sensors. The dense deployment of SAPs also places RF APs closer to the MTs and allows the MTs to transmit at lower power levels. This reduces the energy requirements of IoT devices that would otherwise need to transmit to the central RF AP.

The primary security benefit of VLC lies in the physical properties of light. The inability to penetrate opaque objects and the directionality of the VLC signal provide innate physical layer security. Specifically, the potential for sniffing attacks is reduced since any device looking to intercept the signal would need to be in close proximity. In this way, IoT devices can access dynamic security keys sent via VLC and use them to encrypt data transmitted over the RF interface.

Even if VLC data rates have minimal impact on overall capacity, CSMA/SS can improve RF utilization when the RF channel operates under heavy contention. Figure 2 shows average channel utilization when 50 devices are randomly distributed amongst 1, 2, 3, or 4 sectors and when MTs are evenly distributed amongst sectors. When evaluating use of multiple sectors, utilization is averaged over 500 Monte Carlo trials. As a simplified model, we evaluate an unslotted ALOHA with sector scheduling. Utilization of sector i is

$$S_i = \alpha_i G n_i e^{-2Gn_i} \qquad (1)$$

where α_i is the percentage of time sector i is active, G is traffic load per MT, and n_i is the number of MTs in sector i. Average channel utilization is shown as a function of G. The results show how adding sectors can improve utilization as the per device demand increases. Average utilization with randomly distributed MTs is also shown to come close to the utilization with uniformly distributed MTs. The dotted black line shows an adaptive example where the number of sectors changes from 1 to 2 to 4 as the demand increases.

Time is evenly allocated to sectors in these results; however, the random distribution of MTs can lead to scenarios

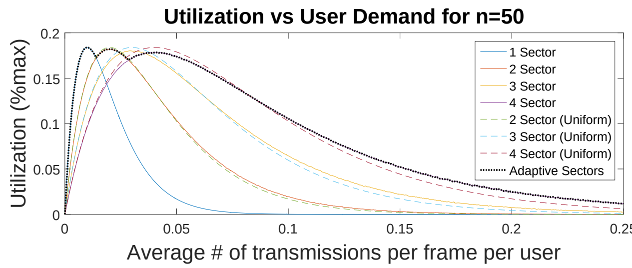

Figure 2. RF utilization with sector scheduling.

where certain sectors have higher demand and fairness is not met across MTs in different sectors. By adapting α_i, we can improve fairness and utilization for the traffic distribution in a given instance. With CSMA/SS, demand can be centrally monitored and related to the active sector without direct knowledge of the MTs. Load balancing between uplink and downlink traffic can also be achieved by assigning time where no sectors are active such that only APs and non-sectored MTs compete. Given the ability to dynamically steer the VLC signal and/or modify the beam width, the coverage area of sectors can also be adapted when demand for a specific sector is disproportionally high. Utilization gains will depend on the percentage of traffic from non-sectored MTs and scenarios where some sectors don't fully utilize the channel during their active time may decrease utilization. This can be resolved by giving active sectors channel priority (e.g., decreasing the DCF interframe space) rather than having MTs only transmit if their sector is active.

4 Conclusions

In conclusion, we present a novel architecture that utilizes low data rate VLC to improve the security and utilization of a shared RF medium. The system also offers IoT devices a means of improved self-sustainability through dual-use energy harvesting VLC receivers and reduced transmit power requirements. We show how sector scheduling can be used to improve upon traditional shared access techniques when the system is operating under heavy contention. Most importantly, the proposed CSMA/SS technique combines the benefits of distributed CSMA techniques and more centralized multiple access techniques while removing the need for the centralized controller to have direct knowledge of the distributed devices in the system.

5 Acknowledgment

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