LiSCAN: Visible Light Uni-Directional Control Channel for Uplink Radio Access

Sharan Naribole* and Edward Knightly†
*Samsung Semiconductor, Inc., San Jose CA USA
†Rice University, Houston TX USA

***Abstract*—Contention-based uplink radio access might lead to significant degradation in airtime efficiency and energy efficiency as the time spent "awake" by the radio is dependent on the network traffic conditions. In this paper, we design and evaluate LiSCAN, a visible light uni-directional control channel for contention-free uplink radio access. LiSCAN enables a virtual full-duplex operation by broadcasting polling frames (light-polls) across distributed LED luminaires concurrently with data reception over radio. In LiSCAN, each client consists of an additional low-power light sensor, which upon hearing a light-poll directed to it by Access Point (AP), wakes up the radio module only if there is backlogged traffic. To maximize the airtime efficiency, LiSCAN transmits light-polls successively until it detects an uplink radio transmission. LiSCAN's pipelined polling enables clients to detect failure in uplink packet reception and accordingly abort their transmissions to eliminate collisions at the AP. We simulate LiSCAN and alternate strategies in ns-3 network simulator to analyze LiSCAN's performance under varying traffic conditions. Our results show that LiSCAN can provide significant improvements in the radio airtime efficiency, the sessions delivered with pre-defined service quality requirements and energy savings.**

I. Introduction

Sensors have becoming a leading solution in many important applications such as industrial automation, smart buildings, telemedicine, etc. A wireless sensor network typically consists of a large number of small, low-cost sensor nodes distributed in the target area for collecting data of interest. The data flow in such networks is mainly in the uplink direction from the sensors to the Access Point (AP). These sensors are often powered with batteries, therefore energy-efficiency is extremely important. To reduce the energy consumption, the key idea of numerous power management mechanisms used in existing works is based on alternating the sensor between two states: awake and sleep. As illustrated in the Fig. 1, the radio is turned on only when there is new traffic enqueued at the sensor. The figure illustrates ongoing transmissions on the radio band and the yellow arrow represents the timestamp at which the sensor enqueues a new frame for transmission. Accordingly, the sensor takes part in the contention-process and transmits its data as shown by the green data frame. After the transmission, the radio can be turned off. Due to the contention process, the time for which sensor is awake is dependent on the network traffic conditions. This uncontrollable access delay might also lead to failure in meeting the quality-of-service requirements typical for sensors related to safety e.g., alarms, gas leak detection, etc.. Moreover, the energy consumption by the sensor's radio module is also dependent on the access delay.

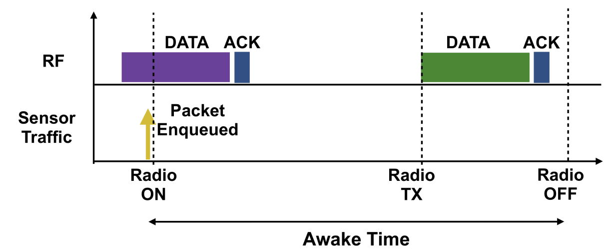

Fig. 1: Radio awake time on sensor.

In an ideal scenario, the AP has perfect knowledge of when the sensors would generate traffic. In such a scenario, the AP can trigger [1] a sensor to turn on its radio only when the sensor has backlogged traffic leading to the sensor transmitting its backlogged data immediately without contention. Unfortunately, the traffic generation at the sensors follow asynchronous patterns. Therefore, the AP lacks perfect knowledge of each sensor's internal state [2], [3] : (a) whether the sensor is backlogged and (b) if backlogged, the size of backlogged data. Instead of making the operation efficient, such control triggers to hundreds of sensors might consume significant airtime over the radio band as majority of the sensors being polled might not have any backlogged data. This inefficiency is expected to increase with increase in the network size.

In this paper, our objective is to maximize the throughput delivered to the AP incorporating the channel access delay and the energy consumption by the sensors. We define this access delay as the radio airtime spent by the sensor for medium access to transmit backlogged data. To achieve the objective, we propose LiSCAN, a visible light communication (VLC) uni-directional control channel for contention-free uplink radio access and make the following contributions:

VLC Uni-Directional Control Channel for Concurrent Transmissions. Our key strategy for reducing the access delay and energy consumption is to transfer the AP's polling to an out-of-band channel. In such a system, the AP doesn't need an ongoing uplink data transmission over radio to end before transmitting poll to next sensor in schedule. Moreover, the sensor's radio module can be turned on only for the data transmission. Due to the severe spectrum scarcity in Wi-Fi bands [4], [5], sensors' antenna, and power limitations [6], utilizing an additional radio channel exclusively for polling control becomes infeasible. In contrast, LiSCAN utilizes visible light communication (VLC) for uni-directional out-of-band control. VLC is well-suited for energy-efficient operation by dual purposing LED-based lighting infrastructure for both illumination and communication. In particular, ceiling-mounted luminaries can modulate lighting in a manner unnoticeable to the human eye (i.e., flicker free) for reception at sensors fitted with energy-autonomous low-power wake-up VLC receivers that consume negligible energy from the sensor's battery [7], [8]. In LiSCAN, the sensors transmits any backlogged data over radio leading to a uni-directional polling system wherein polls are transmitted over VLC and data is transmitted over radio.

We integrate the VLC and radio bands at the MAC layer [1] to enable concurrent near-zero latency communication across the two bands. Similar to 802.11 PCF, in LiSCAN, the AP begins contention-free period by gaining access to both RF and VLC channels. To enable simultaneous poll transmission and data reception at the AP, in LiSCAN, the AP exclusively transmits polls over VLC (*light-poll*) and is in receive mode (RX) over radio.

Pipelined Polling for Overhead Minimization. In 802.11 PCF, a significant part of the polling overhead includes the airtime spent in poll transmission and wait time during which no other transmission is allowed to take place (81.8%). To minimize this overhead, first, we transmit light-poll for next sensor immediately after polling the current sensor. To avoid collisions arising out of data transmissions from multiple sensors, LiSCAN simply aborts transmission of the ongoing light-poll for next sensor upon AP's detection of data transmission from the current sensor. Second, after a successful reception of a data frame, the AP transmits the ACK over VLC instead of radio to eliminate the overhead from the AP's radio switching from receive to transmit mode and back. Third, if the light-poll to next sensor in schedule was aborted due to an ongoing data transmission, our goal is to minimize the radio airtime spent idly during the retransmission of this light-poll. We achieve this objective by aligning the end of light-poll retransmission with the AP's ACK transmission.

Pre-emptive Interference Avoidance. In 802.11 PCF, when the AP doesn't detect an uplink data transmission due to channel fading/interference, it continues transmitting polls based on the schedule. This might lead to severe performance degradation and radio airtime lost due to collisions at the AP. In LiSCAN, when AP doesn't detect an uplink data transmission, it fully transmits the light-poll to next sensor in schedule without abortion. To avoid collision at the AP, upon hearing the light-poll to next sensor, the sensor currently transmitting data to AP aborts its ongoing transmisssion. In this manner, LiSCAN improves the radio airtime utilization.

LiScan Performance Analysis. We simulate the key components LiSCAN in ns-3 network simulator and analyze LiSCAN's performance under varying traffic conditions including varying sensor sizes and bursty traffic parameters.

The remainder of the paper is organized as follows. In Section II, we present the background discussing the 802.11 contention-free access timeline and 802.11 packet detection mechanisms. In Section III, we present LiSCAN's architecture. In Section IV, we present LiSCAN's protocol design and timeline. In Section V, we briefly describe the simulation models utilized for performance analysis. In Section VI, we discuss the key results from our evaluation of LiSCAN. In Section VII, we review related work and we conclude the paper in Section VIII.

II. Background

In this section, we briefly describe the contention-free access mechanism in 802.11 standard. 802.11 Point-Coordination Function (PCF) enables the AP capability to provide centralized contention-free access to the sensors. The periods of contention-free service are alternated by the standard random access contention periods. PCF begins with the AP aggressively gaining access to the channel by transmitting a 802.11 contention-free period (CFP) beacon that includes the maximum possible duration of the current contention-free period. Accordingly, the sensors set their timer to defer from contention-based access. The AP maintains a polling list of associated stations and typically polls in a *round-robin* manner. For efficiency, acknowledgement for received frames at the AP and polling of immediate next sensor may be combined. If a polled sensor has no backlogged data, the sensor does not transmit any frame and the AP transmits next poll request after PIFS duration (25 μs). This PIFS duration includes *(a)* one slot time (9μs) consisting of preamble-based packet detection duration and *(b)* SIFS duration (16μs) for AP to switch from receive mode to transmit mode. The contention-free period ends when the AP transmits a CF-End management frame leading to the start of a contention period.

III. LiSCAN Architecture

In this section, we present the design principles of LiSCAN's hardware and software architecture to enable VLC uni-directional control for uplink contention-free access. Moreover, we discuss an example deployment scenario and protocol stack.

A. Hardware and Network Architecture

We design an indoor WLAN [1] that dual purposes luminaries for communication. A typical deployment scenario as illustrated in Fig. 2 has multiple LED lighting sources used to illuminate a room. The luminaries are typically distributed spatially solely for illumination objectives in order to avoid large shadows associated with a single point source. To enable maximum reliability of light-poll, the LiSCAN AP controls these LEDs and groups multiple sources together as a single broadcast transmission. The AP is only required to transmit but not receive via VLC, as the LiSCAN AP need not be equipped with photo diodes. For the downlink data transmission and uplink reception, the LiSCAN AP utilizes legacy Wi-Fi hardware and custom software as described below.

LiSCAN sensors are equipped with a VLC wake-up receiver system [7], [8] for reception of VLC signals. The LiSCAN sensor uses VLC for all downlink polling control barring outage or failure. At the same time, LiSCAN sensor uses legacy Wi-Fi hardware and custom software for uplink control (such as ACKs and channel state reports) and data.

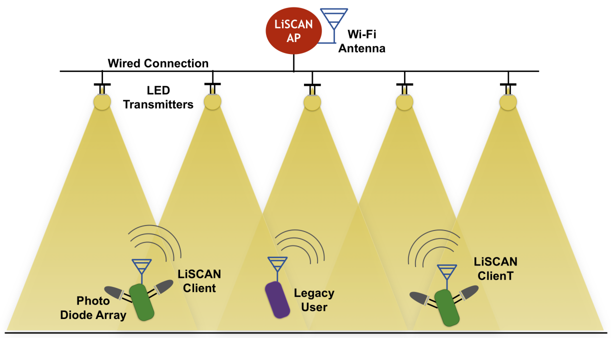

Fig. 2: Example LiSCAN scenario.

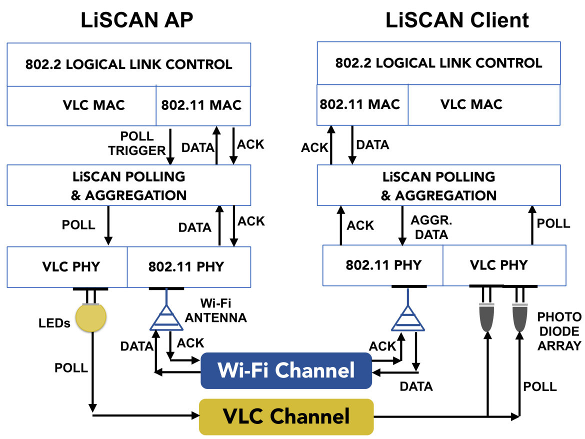

Fig. 3: LiSCAN architecture and polling traffic flow.

B. Software and Protocol Stack

LiSCAN consists of a side-by-side light-radio protocol stack integrated via a common IEEE 802.2 interface. Consequently, as illustrated in Fig. 3, LiSCAN provides an abstraction of a single layer-2 hardware interface to higher layers. The unified interface is critical to realizing a fast VLC control channel for uplink Wi-Fi transmissions. From the data flow perspective, the polling for LiSCAN sensors is performed over VLC only. The light-polls are transmitted at the base rate similar to a poll transmission over radio. The primary functions of the VLC downlink MAC are scheduling, framing, and PHY adaptation. The VLC MAC is not contention based as ambient light sources not controlled by the AP are considered to be interference. LiSCAN can employ any physical layer, including [9]–[11]. Frames addressed to the sensor are processed up the protocol stack as illustrated in the figure.

Uplink data frame is transmitted via legacy Wi-Fi in the same way that legacy stations transmit. Moreover, uplink data is acknowledged by the LiSCAN AP using VLC to minimize the radio airtime overhead involved in AP switching from receive mode to transmit mode and back. In this manner, AP can transmit ACK over VLC as soon as it completes decoding a received data frame over radio. For backward compatibility, AP still has the capability to transmit ACK over radio for legacy sensors and perform regular 802.11 operation during contention-based access periods. Because the sensor only transmits backlogged data in response to AP's light-poll, we employ frame aggregation for all the frames forwarded from the 802.11 MAC to the LiSCAN Polling and Aggregation sub-layer. This is in contrast to polling the sensor multiple rounds wherein each round the sensor only transmits a single frame.

IV. LiSCAN Design

Utilizing the virtual full-duplex operation of VLC (transmit mode) and radio (receive mode) at AP, LiSCAN minimizes the radio airtime overhead. In this section, we present the key concepts of LiSCAN's pipelined VLC polling. Second, we analyze the bounds of overhead reduction achieved by LiSCAN.

A. LiSCAN's Pipelined VLC Polling

To realize a scalable contention-free uplink access by polling over VLC, we design LiSCAN whose timeline is illustrated in Fig. 4. The key strategies of LiSCAN are as follows:

Initial VLC-RF Alignment. In LiSCAN, the AP begins CFP by gaining access to both RF and VLC channels. Over RF, similar to 802.11 PCF, AP aggressively transmits a beacon frame PIFS duration after channel becomes idle to broadcast start of CFP. Throughout the contention-free period in LiSCAN, the sensors are solely in transmit mode on Wi-Fi radio and the AP is solely in receive mode over Wi-Fi. This is to eliminate the time spent in switching from transmit mode to receive mode and vice versa. To minimize the airtime lost in RF while transmitting light-poll to first sensor in schedule, our key strategy is to *align* both the transmissions such that light-poll to first sensor in schedule ends SIFS duration after the end of CFP start beacon. This scenario represents CFP start beacon over RF and light-poll to sensors A in Fig. 4. The additional SIFS duration is required for sensor A to switch from receive to transmit mode.

Pipelined Polling. A simple approach (as in 802.11 PCF) to poll the next sensor in schedule is to wait until the occurrence of the following event: *(i)* the end of an ongoing data- ACK exchange or *(ii)* wait for PIFS duration (includes one slot time for packet detection and SIFS duration for AP RX-to-TX switch). Clearly, this can lead to significant polling overhead when only a small percentage of sensors have backlogged data. In LiSCAN's design, we take advantage of the virtual full-duplex operation of VLC (transmit mode) and radio (receive mode) at AP. Our key strategy is to transmit light-poll to next sensor in schedule immediately after end of light-poll to the current sensor. Also, at the end of a light poll transmission, we begin a packet detection countdown timer that begins from an initial value matching the packet detection time (20 μs in IEEE 802.11). Depending on whether the AP detects an uplink transmission or not, LiSCAN behaves in the following manner:

(a) No packet detected. If the current sensor (sensor A) has no backlogged data, then it won't transmit any data corresponding to the light-poll it receives. Consequently, the

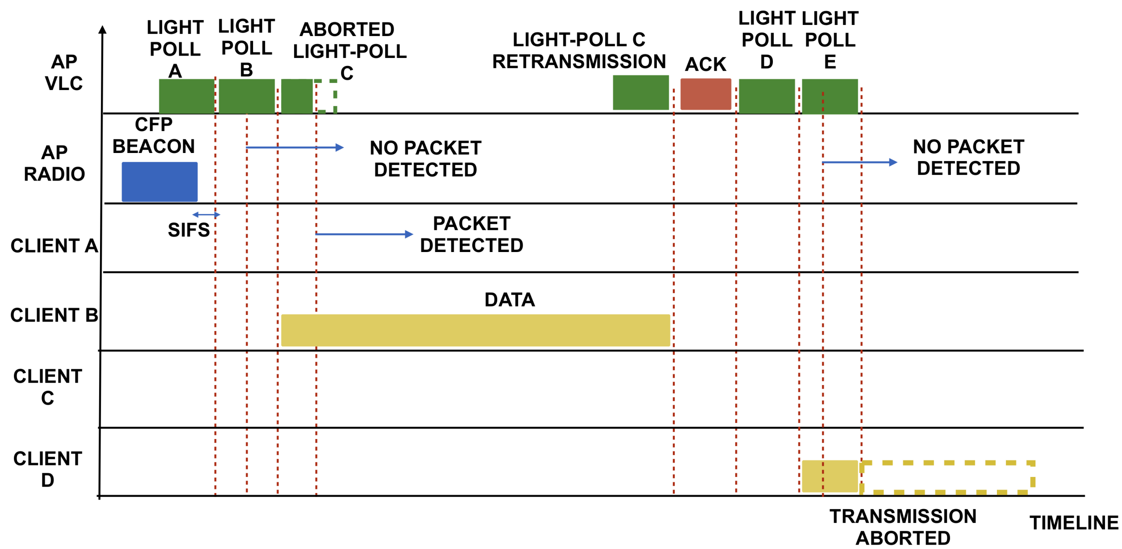

Fig. 4: LiSCAN contention-free period timeline.

AP fully transmits the light-poll for next sensor (sensor B) with no abortion as it does not detect any 802.11 frame. Upon hearing its light-poll, the next sensor can transmit any backlogged data as soon as it decodes the VLC poll. In this scenario, LiSCAN eliminates the overhead involved in waiting for detection of uplink data frame before transmitting next light-poll. This scenario represents light-polls to sensor A and sensor B in Fig. 4.

(b) Packet detected. As soon as the AP detects the current sensor's (sensor B) transmission, it computes the transmission time of the ongoing uplink frame from sensor B. If this transmission time is longer than that of the ongoing light-poll transmission to next sensor (sensor C), the AP will immediately abort the light-poll transmission. As the light poll transmission time is longer than the 802.11 packet detection (20μs), the light poll to next sensor is not fully transmitted before abortion. In future, if the VLC rate becomes faster, additional payload can be added to ensure the transmission time of light-poll is at least longer than the 802.11 packet detection time. Consequently, the next sensor does not transmit any backlogged data. Through this light-poll abortion, we prevent any uplink collisions at the AP. This scenario represents light-polls to sensors B and C in Fig. 4.

ACK over VLC. In LiSCAN, we utilize VLC instead of radio for ACK transmissions corresponding to successful uplink data reception. This serves two purposes: First, by transmitting over VLC, LiSCAN eliminates the radio airtime lost in AP switching from receive mode to transmit mode for ACK transmission and back to receive mode for future data reception. Second, by transmitting over VLC, the next sensor in schedule can transmit backlogged data over radio concurrently with ACK transmission over VLC. To achieve this, LiSCAN utilizes the PHY header of ongoing uplink data transmission to find out the time at which this transmission ends. As the light-poll to next sensor in schedule was aborted upon hearing the ongoing transmission's preamble, LiSCAN begins the retransmission of next sensor's light-poll to end at the same time as ongoing uplink transmission. In this manner, if the next sensor has backlogged data, it can begin the data transmission as soon as it decodes the light-poll. Concurrently, the AP can transmit the ACK if it successfully receives the uplink data frame. Accordingly, the next light-poll will be transmitted after the ACK transmission. On the other hand, if the AP doesn't receive the frame successfully, then it won't transmit an ACK and the next light-poll in schedule is transmitted immediately after decoding reception failure. In Fig. 4, we illustrate the alignment of light-poll to sensor C with the end of data transmission from sensor B. After successful decoding of sensor B's data, AP transmits the corresponding ACK over VLC followed by light-poll to sensor D.

Preemptive Uplink Interference Avoidance. sensors' uplink transmissions could suffer from channel fading or co-channel interference from neighboring Wi-Fi cells and other co-existing technologies. In 802.11 PCF, when the AP fails to detect the preamble of a sensor's uplink transmission, it waits for PIFS duration before transmitting next poll. If the next sensor has backlogged data and transmits to the AP, it would lead to reception failure at the AP due to the multiple concurrent uplink transmissions. In a saturated traffic scenario, such interference can lead to significant loss in radio airtime. In LiSCAN, for the same scenario of preamble detection failure, the AP assumes there is no data transmission from current sensor and consequently completes the transmission of light-poll to the next sensor without abortion. To prevent collision at the AP, in LiSCAN, the current sensor pre-emptively aborts its ongoing data transmission upon hearing a *fully-transmitted* light-poll to next sensor. In this manner, LiSCAN eliminates collision of uplink data transmissions from multiple sensors due to preamble detection failure. This scenario is represented by the abortion of data transmission from sensor D on hearing the light-poll for sensor E.

B. Packet Detection Sensitivity

An important component of LiSCAN is the uplink packet detection. When an uplink packet is detected, LiSCAN aborts the light-poll transmission before it is fully transmitted. The physical carrier sensing in 802.11 is conducted by the Clear Channel Assessment module that determines the idle/busy status of the radio channel. OFDM PHY Clear Channel Assessment utilizes the amount of received energy at the Radio-Frequency module and preamble-based detection to detect valid 802.11 signals. The initial part of the preamble consists of ten identical sequences of Short Training Symbols of length 16 samples each of duration 0.8 μs obtained by OFDM modulation of known pseudo-random noise (PN) sequences. The AP can detect the start of an 802.11 packet by correlating the received signal with known PN sequences. The key advantage of a PN sequence is the sharp distinct peak that it provides exactly when the input signal to the correlator matches the PN sequence. The IEEE 802.11 standard mandates that, when a 802.11 receiver senses a 802.11 signal whose energy is above the Clear Channel Assessment threshold of - 62 dBm, the preamble detection probability has to be $\geq$ 90% in an observation time window of 4μs.

In our scenario, even when a sensor is transmitting a valid 802.11 frame to the AP, strong interference on the same radio channel might lead to failure in packet detection at the AP. In Section VI, we show that LiSCAN's pre-emptive interference avoidance helps minimize the performance degradation due to packet detection failure at the AP independent of the interference level.

C. Light-Poll Analysis

In 802.11 PCF, the radio airtime lost in polling a non-backlogged sensor is the sum of poll transmission time and PIFS duration of idle waiting (135μs). A significant percentage (81.5%) of this lost time is spent in the transmission of poll. In contrast, by transmitting the next light-poll in a pipelined manner can provide significant reductions in overhead. Next, we analyze the overhead reduction brought about by LiSCAN for different scenarios.

Standard Specification	Value
Poll Payload	418 bits
Preamble	124 bits
PHY header	32
Modulation	On-Off Keying
Min. Optical Clock Rate	15 MHz
Lowest data rate	6 Mbps

TABLE I: 802.15.7 frame timing and data rates.

To compute the poll transmission time over VLC, we utilize the same polling payload size as in 802.11 PCF. We incorporate the rest of the frame components sizes and data rates as defined in the 802.15.7 standard and provided in Table I. The preamble and headers are required by the standard to be transmitted at the lowest data rate for a chosen optical clock rate. Assuming the same rate of 6 Mbps as chosen for 802.11 PCF, the transmission time of a light-poll is equal to 110μs. Next, we discuss the range of radio airtime spent idly during light-poll transmission:

(i) Best case: This represents the light-poll to sensor C that aligns its end with the end of data transmission from sensor B in Fig. 4. Therefore, sensor C can transmit any backlogged data immediately resulting in zero airtime lost. When most sensors in the network have fully backlogged traffic, LiSCAN incurs zero radio airtime for light-poll transmissions thus achieving maximum efficiency.

(ii) Worst case: This represents the light-poll to sensor B following the light-poll to sensor A in Fig. 4. As sensor A had no backlogged data, there is no poll reply from sensor A. Therefore, the radio channel is idle during the entire transmission of light-poll to sensor B. In this case, this is equivalent to a poll transmission over RF. However, LiSCAN might still reduce the overhead in case sensor B has no backlogged data. This is because in LiSCAN the light-poll for sensor C immediately follows light-poll for sensor B instead of waiting for PIFS duration as in 802.11 PCF.

(iii) Interference case: In case of preamble detection failure of an uplink data frame, the AP doesn't abort the light-poll to next sensor. As that uplink data frame will be aborted after the sensor receives the light-poll for next sensor, this data does not account for successful data received by AP. Therefore, this light-poll transmission to next sensor will be considered as radio airtime overhead and is equivalent to the worst case described previously.

V. LiSCAN Implementation

To analyze LiSCAN's performance for varying network conditions and to compare it's performance against alternative strategies, we extend the ns-3 network simulator [12]. In this section, we briefly describe our ns-3 extension to analyze LiSCAN and alternative strategies, the traffic generation model at the LiSCAN sensors and radio interference model.

A. ns-3 Extensions

To simulate contention-free access in ns-3, we implement a base ns-3 MAC contention-free access model on top of the existing 802.11g Wi-Fi PHY implementation. For channel fading, we utilize the NIST model, an OFDM error rate model that has been validated using experimental results from physical-layer testbed [13]. We inherit this base contention-free model to implement the different protocols considered in this paper.

B. Uplink Data Traffic Model

To simulate realistic Internet traffic, we utilize the Poisson Pareto Burst Process (PPBP) [14] model that has been validated to match the statistical properties of real-life IP networks. This model is based on the overlapping of multiple traffic bursts. The arrival of each traffic burst follows a Poisson distribution. It has been shown that the distribution of the sizes of files transmitted across the Internet is heavy-tailed [15]. Therefore, the burst length is modeled by Pareto distribution with infinite variance resulting in a long-range dependent traffic model. The Pareto distribution is characterized by a Hurst parameter that defines the shape of the distribution. The typical values for this Hurst parameter lie between 0.5 and 0.9.

As our focus is on contention-free access for uplink data transmissions, we consider packets arrive at the uplink MAC queue of each sensor independently following the PPBP model. In LiSCAN, under high traffic conditions, the light-polls are transmitted concurrently with uplink data transmission resulting in a low overhead. To analyze the overhead reduction in comparison to Contention-free radio access, in our simulations, we consider varying mean burst arrival rates at the sensors.

C. Network Model for Analysis

Using the models described above, we perform simulations under varying network conditions of sensor size, the percentage of sensors with traffic during the contention-free period and the mean burst arrival rate. We fix the mean burst time length of PPBP process to a value of 10 milliseconds. We consider 10 bytes generated by the burst process model and with a maximum aggregation of 100 bytes for data transmission. For each combination of network conditions, we perform over 1000 runs of 100 ms each separately for LiSCAN and alternative strategies. We consider the polls, light-polls and ACKs are transmitted at the base rate of 6 Mbps. For the uplink data transmission, we consider the sensors can transmit at 54 Mbps. In each contention-free period for both LiSCAN and Contention-free radio access, the polling is performed in a round-robin manner and the schedule is selected randomly using a uniform distribution. For each run, we obtain the following performance metrics:

Mean channel access delay. We define channel access delay as the time between a packet arrival to sensor's uplink MAC queue and corresponding over-the-air transmission. The mean channel access delay of a contenton free period run is the mean of channel access delay across every uplink data packet transmitted during the run.

Throughput. We define the throughput in a contention-free period as the total successful uplink data received by the AP divided by the duration of the contention-free period.

Energy Consumption. The mean energy consumption for which the radio module of a sensor is awake. In LiSCAN, the sensor is awake on the radio only for the data transmission. In contrast, in the alternative strategies, the radio is awake whenever there is backlogged traffic and for the data-ACK exchange. For the contention-based access, we utilized the existing ns-3 WiFi Radio Energy module. For the energy consumption in contention-free strategies, the power consumption in different states of sensor was modeled utilizing existing research works [16]–[18].

VI. Performance Evaluation

With increasing number of sensors generating traffic, we expect negligible change in the polling overhead for LiSCAN and contention-free radio access. This is because the AP is oblivious of the traffic generation at the sensors and therefore includes every sensor in its polling schedule. In contrast, in contention-based access, only the sensors generating traffic take part in the contention procedure. With increasing traffic burst arrival rate at the sensors, we expect the probability of a polled sensor to have backlogged data to increase leading to increased radio channel utilization for contention-free strategies. In this section, we analyze LiSCAN's performance under varying network conditions and also compare its performance with alternative strategies. Unless stated otherwise, for every figure in this section: (a) each sub-plot corresponds to a particular ratio of the sensors generating any traffic and (b) the x-axis in each sub-plot represents the varying mean burst arrival rate at the sensors generating traffic during a runtime of 100 milliseconds. We define the ratio of sensors generating any traffic during a run as *sensor ratio*.

A. Radio Access Delay

In Fig. 5, we analyze the impact of the sensor ratio and the traffic arrival rate on the channel access delay. With low traffic burst rates and low sensor ratio, the contention-based access has the lowest access delay as the sensor generating traffic does not suffer from collisions and binary exponential backoff. In contrast, the radio-only contention free strategy has the highest delay as significant airtime is spent in polling sensors with no traffic. With moderate to high traffic burst rates independent of the sensor ratio, contention-based approach incurs a steep increase in access delay. This is because of the increased contention-based collisions and consequent exponential backoff for retransmissions. In contrast, there is only a slight increase for the contention-free strategies as they do not suffer from collisions. The slight increase in contention-free strategies is due to the increased radio utilization for uplink data transmission.

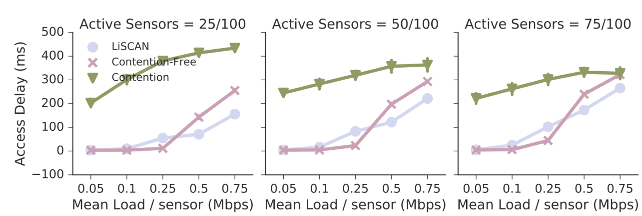

Fig. 5: Mean channel access delay vs traffic burst arrival rates for varying sensor ratios.

B. Throughput

In Fig. 6, we analyze the impact of the sensor ratio and the traffic arrival rate on the aggregate uplink throughput at the AP. With low sensor ratio, independent of the traffic burst rate, the contention-based access provides the highest throughput. This is because the contention-based strategies spend significant airtime polling sensors with no backlogged traffic. With moderate to high traffic rates, we observe LiSCAN provides significant improvement in throughput compared to other strategies. Unlike contention-based access, the sensors in LiSCAN do not contend and transmit their data as soon as they receive a light-poll intended for them. Unlike radio-only contention, the increased radio utilization enables LiSCAN to transmit the light-polls and ACKs over VLC concurrently with uplink radio transmissions. In this manner, LiSCAN increases the radio airtime for uplink data transmissions compared to radio-only contention-free strategy.

Finding: LiSCAN's virtual full-duplex operation provides up to 5 times higher aggregate throughput over contention-based strategy during high traffic conditions in dense sensor networks.

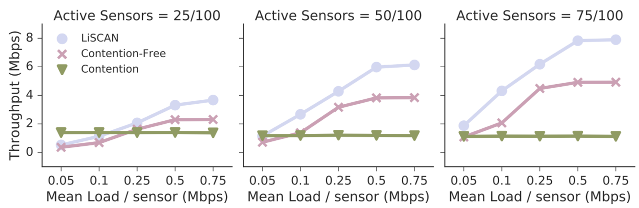

Fig. 6: Aggregate throughput vs traffic burst arrival rates for varying sensor ratios.

C. Energy Consumption

In Fig. 7, we analyze the impact of the sensor ratio and the traffic arrival rate on the mean time for which the radio is awake in LiSCAN. First, independent of the sensor ratio and traffic rate, the mean awake time of a sensor in LiSCAN is less than 0.5 ms for a contention-free period of 100 ms (less than 0.5%). This low awake time is due to the radio module of a sensor being turned on in LiSCAN only for the uplink data transmission. Even if the sensor has backlogged traffic, the wake up receiver keeps the radio off until receiving a light-poll intended for this sensor. Moreover, the VLC wake-up receiver receives the ACK for a just concluded uplink data transmission instead of the sensor's radio. Second, for a given traffic ratio, the mean awake time increases with increasing sensor ratio. This is because of the increased number of sensors generating traffic during the contention-free period. Third, with increasing traffic rates, the awake time increases as the data generated by sensors generating any traffic increases.

Finding: LiSCAN's utilization of VLC channel for radio control results in near-zero energy consumption on the radio channel.

In Fig. 8, we compare the radio awake time of LiSCAN and other strategies for varying traffic rates and sensor ratios. First, compared to LiSCAN, the radio-only strategies have significantly higher awake time. This is because the radio of a sensor is on (a) when it has backlogged traffic, (b) uplink transmission and (c) ACK reception. Second, for low and moderate sensor ratios, the contention-based approach has higher awake time during high traffic rates because of

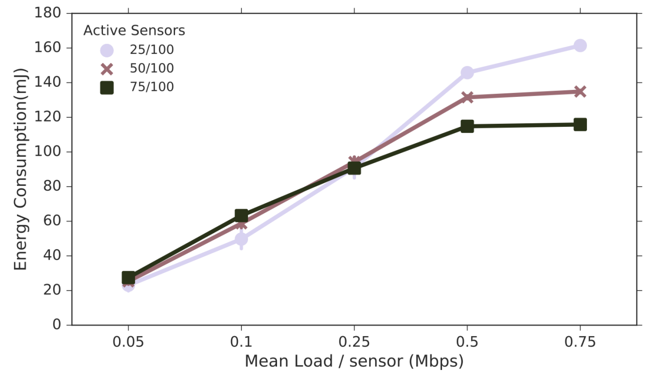

Fig. 7: Mean energy consumption per active sensor in LiSCAN vs traffic burst arrival rates for varying sensor ratios.

increased waiting time during contention. Third, when the sensor ratio is high and the traffic rate is high, we observe both the contention-based and contention-free strategies converge in their radio awake time. This is because of the increased data generation in the radio only contention-free strategy.

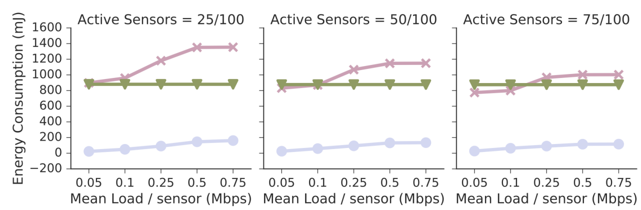

Fig. 8: Mean energy consumption per active sensor vs traffic burst arrival rates for varying ratios of sensors with traffic. Legend is same as in Fig. 6.

VII. Related Work

Wake-up Radios. In-band asynchronous energy-saving MAC protocols have been proposed in literature [19], [20]. To further reduce the energy consumption, several works have proposed the use of additional low-power radio to aid the sensor's wake up [21], [22]. Recently, IEEE 802.11 working group has established the IEEE 802.11ba project focusing on wake-up radios [23]. First, due to the spectrum scarcity, the efficiency of this operation might be significantly degraded in dense deployments considered in this paper. Second, a wake-up radio typically remains always active and consume energy from the attached sensor. In contrast, the illumination coverage of LED luminaires naturally provides improved spatial reuse even in dense deployments and the energy-autonomous nature of the wake-up VLC receivers [7], [8] leads to negligible impact on the sensor's energy.

QoS-aware Scheduling. Protocols such as Hybrid Coordination Function (HCF) [24] in IEEE 802.11e standard and trigger-based uplink OFDMA in IEEE 802.11ax standard [25], [26] have extended 802.11 PCF with QoS-aware scheduling. In such protocols, the AP learns the QoS requirements and backlogged traffic at the clients through a separate contention-based period in 802.11e standard and buffer status reporting in 802.11ax standard. LiSCAN can work in conjunction with such QoS-aware scheduling algorithms to further improve the contention-free period performance.

Integrated VLC-RF Networks. VLC and RF have been jointly used in prior work: load balancing between VLC and RF interfaces was optimized in [27], [28]; horizontal and vertical handover mechanisms between VLC and RF networks were designed in [29]–[31]; In [1], the authors designed LiRa, the first system to integrate VLC and RF at the MAC layer, and the first system to provide a virtual feedback channel for VLC via Wi-Fi. In contrast, LiSCAN is the first system to design a scalable uni-directional VLC control channel for contention-free RF uplink access. Nonetheless, the aforementioned works are complementary to LiSCAN and can be used to enhance LiSCAN at other layers and other WLAN services.

VLC Services and Devices. Lastly, there is an emerging body of research on employing VLC for sensing or localization [32], [33] and also to aid beam tracking and alignment in 60 GHz WLANs [34]. LiSCAN can be deployed in parallel with such applications.

VIII. Conclusion

In this paper, we designed and evaluated LiSCAN, a VLC uni-directional control channel that enables virtual full-duplex contention-free operation of uplink radio access. Our results show that LiSCAN utilizes near-zero energy consumption to provide (a) significant reductions in the radio access delay and (b) 5x improvement in aggregate throughput compared to contention-based radio access.

The authors would like to thank the anonymous reviewers for their helpful and constructive comments. This research was supported by NSF grants CNS-1824529, 1801857, and 1518916.

References

[1] S. Naribole, S. Chen, E. Heng, and E. Knightly, "LiRa: a WLAN architecture for Visible Light Communication with a Wi-Fi uplink," in *Proc. of IEEE SECON*, 2017.

[2] M. A. Al-Maqri, M. Othman, B. M. Ali, and Z. M. Hanapi, "Packet-based Polling Scheme for Video Transmission in IEEE 802.11 e WLANs," *Elsevier Procedia Computer Science*, vol. 83, pp. 337–344, 2016.

[3] R. Viegas, L. A. Guedes, F. Vasques, P. Portugal, and R. Moraes, "A new MAC scheme specifically suited for real-time industrial communication based on IEEE 802.11 e," *Elsevier Computers & Electrical Engineering*, vol. 39, no. 6, pp. 1684–1704, 2013.

[4] A. Jovicic, J. Li, and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," *IEEE Communications Magazine*, vol. 51, no. 12, pp. 26–32, 2013.

[5] J. Chapin and W. Lehr, "Mobile broadband growth, spectrum scarcity, and sustainable competition," *Proc. of TPRC*, 2011.

[6] A. B. Flores, S. Quadri, and E. W. Knightly, "A Scalable Multi-User Uplink for Wi-Fi," in *Proc. of USENIX NSDI*, 2016.

[7] J. S. Ramos, I. Demirkol, J. Paradells, D. Vössing, K. M. Gad, and M. Kasemann, "Towards energy-autonomous wake-up receiver using Visible Light Communication," in *Proc. of IEEE CCNC*, 2016.

[8] C. Carrascal, I. Demirkol, and J. Paradells, "A novel wake-up communication system using solar panel and Visible Light Communication," in *Proc. of IEEE GLOBECOM*, 2014.

[9] D. Tsonev, S. Videv, and H. Haas, "Towards a 100 Gb/s visible light wireless access network," *OSA Optics Express*, vol. 23, no. 2, pp. 1627–1637, 2015.

[10] G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "3.4 Gbit/s Visible Optical Wireless Transmission Based on RGB LED," *OSA Optical Express*, vol. 20, no. 26, pp. B501–B506, Dec 2012.

[11] IEEE Computer Society, "IEEE Standard for Local and Metropolitan Area Networks - Part 15.7: Short-Range Wireless Optical Communication Using Visible Light," September 2011.

[12] T. R. Henderson, M. Lacage, G. F. Riley, C. Dowell, and J. Kopena, "Network simulations with the ns-3 simulator," *SIGCOMM demonstration*, vol. 14, no. 14, p. 527, 2008.

[13] G. Pei and T. R. Henderson, "Validation of OFDM error rate model in ns-3," *Boeing Research Technology*, pp. 1–15, 2010.

[14] D. Ammar, T. Begin, and I. Guerin-Lassous, "A new tool for generating realistic internet traffic in ns-3," in *Proc. of 4th International Conference on Simulation Tools and Techniques*, 2011.

[15] M. E. Crovella and A. Bestavros, "Self-similarity in World Wide Web traffic: evidence and possible causes," *IEEE/ACM Transactions on Networking*, vol. 5, no. 6, pp. 835–846, 1997.

[16] J. M. Molina, J. Haase, and C. Grimm, "Energy consumption estimation and profiling in wireless sensor networks," in *Proc. of VDE ARCS*, 2010.

[17] M. Abo-Zahhad, M. Farrag, A. Ali, and O. Amin, "An energy consumption model for wireless sensor networks," in *Proc. of IEEE ICEAC*, 2015.

[18] W. Du, F. Mieyeville, and D. Navarro, "Modeling energy consumption of wireless sensor networks by systemc," in *Proc. of IEEE ICSNC*, 2010.

[19] E. Shih, P. Bahl, and M. Sinclair, "Wake on wireless: An event driven energy saving strategy for battery operated devices," in *Proc. of ACM MobiCom*, 2002.

[20] T. Rault, A. Bouabdallah, and Y. Challal, "Energy efficiency in wireless sensor networks: A top-down survey," *Elsevier Computer Networks*, vol. 67, pp. 104–122, 2014.

[21] P. Le-Huy and S. Roy, "Low-power 2.4 GHz wake-up radio for wireless sensor networks," in *Proc. of IEEE WiMob*, 2008.

[22] J. Dias, F. Sousa, F. Ribeiro, R. Campos, and M. Ricardo, "Green wireless video sensor networks using FM radio system as control channel," in *Proc. of IEEE WONS*, 2016.

[23] D. Deng, M. Gan, Y. Guo, J. Yu, Y. Lin, S. Lien, and K. Chen, "IEEE 802.11ba: Low-Power Wake-Up Radio for Green IoT," *IEEE Communications Magazine*, vol. 57, no. 7, pp. 106–112, July 2019.

[24] S. Mangold, S. Choi, P. May, O. Klein, G. Hiertz, and L. Stibor, "IEEE 802.11 e Wireless LAN for Quality of Service," in *Proc. of European Wireless*, 2002.

[25] S. Naribole, W. Lee, and A. Ranganath, "Impact of MU EDCA channel access on IEEE 802.11ax WLANs," in *Proc. of IEEE VTC Fall*, 2019.

[26] E. Khorov, A. Kiryanov, A. Lyakhov, and G. Bianchi, "A Tutorial on IEEE 802.11ax High Efficiency WLANs," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 197–216, 2018.

[27] M. Rahaim, A. Vegni, and T. Little, "A Hybrid Radio Frequency and Broadcast Visible Light Communication System," in *Proc. of IEEE GLOBECOM Workshop on Optical Wireless Communications*, 2011.

[28] X. Li, R. Zhang, and L. Hanzo, "Cooperative Load Balancing in Hybrid Visible Light Communications and WiFi," *IEEE Transactions on Communications*, vol. 63, no. 4, pp. 1319–1329, 2015.

[29] X. Bao, X. Zhu, T. Song, and Y. Ou, "Protocol Design and Capacity Analysis in Hybrid Network of Visible Light Communication and OFDMA Systems," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 4, pp. 1770–1778, 2014.

[30] A. Tang, C. Xu, B. Zhai, and X. Wang, "Design and Implementation of an Integrated Visible Light Communication and WiFi System," in *Proc. of IEEE MASS*, 2018.

[31] R. Meister, J. Classen, M. Saud, M. Katz, and M. Hollick, "Practical VLC to WiFi Handover Mechanisms," in *Proc. of International Conference on Embedded Wireless Systems and Networks*, 2019.

[32] Z. Zhao, G. Min, Y. Pang, W. Gao, and J. Lv, "Towards Fast and Reliable WiFi Authentication by Utilizing Visible Light Diversity," in *Proc. of IEEE SECON*, 2019.

[33] C. Zhang, J. Tabor, J. Zhang, and X. Zhang, "Extending Mobile Interaction Through Near-Field Visible Light Sensing," in *Proc. of ACM MobiCom*, 2015.

[34] M. Haider, Y. Ghasempour, D. Koutsonikolas, and E. Knightly, "LiSteer: MmWave beam acquisition and steering by tracking indicator LEDs on wireless APs," in *Proceedings of ACM MobiCom*, 2018.