Project Report: An Optimized Dynamic MAC Protocol for Vehicular Optical Camera Communication Networks

Section 1: The Emerging Landscape of Vehicular Optical Wireless Communication

1.1 Introduction to VLC and OCC in Intelligent Transportation Systems (ITS)

The relentless growth in vehicular connectivity and the advent of autonomous driving systems have created an unprecedented demand for high-bandwidth, reliable, and secure communication channels. Traditional Radio Frequency (RF) based systems, while foundational, face increasing challenges from spectrum congestion and interference. In response, the field of Optical Wireless Communication (OWC) has emerged as a powerful and complementary technology for the next generation of Intelligent Transportation Systems (ITS).[1] OWC leverages the vast, unlicensed visible light spectrum, ranging from 380 nm to 780 nm, to transmit data, offering a pathway to alleviate RF spectrum scarcity.[3]

Within OWC, two key technologies are particularly relevant. Visible Light Communication (VLC) is the broader field, encompassing any use of visible light for data transmission, often achieving high data rates through specialized photodiodes.[2] A highly pragmatic and promising sub-field for vehicular applications is Optical Camera Communication (OCC). OCC utilizes the components already becoming standard in modern vehicles and infrastructure: Light-Emitting Diodes (LEDs) as transmitters and digital cameras as receivers.[5] This approach is exceptionally cost-effective, as it repurposes existing hardware for a dual purpose of illumination and communication.[7]

The integration of OCC into the vehicular environment enables a rich ecosystem of communication modalities, including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Infrastructure-to-Vehicle (I2V) links.[1] In this paradigm, a vehicle's camera can receive data from the headlights and taillights of surrounding cars, as well as from LED-based traffic signals and streetlights. This ubiquitous deployment of potential transmitters and receivers makes OCC a compelling solution for building the dense, data-rich networks required for advanced driver-assistance systems and future autonomous navigation.[6]

1.2 Unique Advantages and Inherent Challenges of Vehicular OCC (V-OCC)

The adoption of OCC in vehicular networks, or V-OCC, is driven by a unique set of advantages that directly address the shortcomings of RF systems. The directional, line-of-sight (LoS) nature of light provides inherent security, as it is difficult to eavesdrop on a signal without being physically present in the light cone.[5] This directionality also grants V-OCC a high degree of immunity to electromagnetic interference and allows for a high spatial reuse factor, meaning multiple, dense communication links can operate in close proximity without interfering with one another—a crucial feature for congested traffic scenarios.[1]

However, these same physical properties also introduce significant challenges that must be overcome for V-OCC to be a viable technology. The primary challenges are:

- **Mobility and Dynamic Topology:** Vehicular networks are defined by their high degree of mobility and constantly changing topologies. The rapid movement of vehicles alters link geometries, affects signal strength, and can lead to frequent connection interruptions. The communication protocol must be robust enough to handle these dynamic channel conditions.[1]
- **Line-of-Sight (LoS) Blockages:** The reliance on LoS means that communication links can be easily and abruptly broken by obstacles, such as other vehicles, buildings, or even adverse weather conditions. Protocols must therefore be capable of rapid link re-establishment or dynamic routing to maintain connectivity.[11]
- **Limited Data Rate:** While VLC can achieve very high speeds, OCC, being limited by the frame rate and processing capabilities of cameras, offers a comparatively low data rate. Studies report achievable rates in the range of a few kilobits per second (e.g., 3-4 kbps), which makes efficient use of the available bandwidth absolutely critical.[5]

- **Environmental Factors:** The V-OCC performance is sensitive to environmental conditions. Strong ambient light, particularly solar irradiance, can saturate camera sensors and degrade the signal-to-noise ratio, potentially disrupting communication links.[13] The algorithm presented in this project acknowledges this by incorporating weather state as a primary eligibility condition for OCC usage.[14]

1.3 The Criticality of the MAC Layer in V-OCC

A thorough analysis of V-OCC's characteristics reveals that the most significant bottleneck to its widespread, reliable deployment lies not at the physical (PHY) layer, but at the Medium Access Control (MAC) layer. The PHY layer defines *how* a single bit is transmitted, but the MAC layer dictates *who* gets to transmit and *when*. In an environment with a scarce resource—in this case, the low intrinsic bandwidth of OCC—any inefficiency in how that resource is shared has a disproportionately severe impact on overall network performance.

The logic proceeds as follows. First, the data rate of V-OCC systems is fundamentally constrained by camera technology, resulting in a low-bandwidth channel measured in kilobits per second.[5] Second, the target applications for vehicular communication, such as cooperative awareness messages, platooning, or emergency electronic braking, demand extremely high reliability and predictably low latency.[1] Transmitting critical safety information with a delay of even a few hundred milliseconds can render it useless.

Given this context, the focus of the Optimized DynaVLC project on MAC layer parameters—specifically the Multi-superframe Order (MO), Superframe Order (SO), and dynamic CAP reduction—is not merely an incremental improvement but a critical enabling strategy.[14] In a low-bandwidth system, every wasted time slot, whether due to a data packet collision, excessive protocol overhead, or inefficient resource allocation, represents a significant percentage of the total available capacity. Therefore, an intelligent MAC protocol that can minimize this waste by dynamically adapting to network conditions is essential. The DynaVLC algorithm addresses this fundamental challenge by creating a system that actively manages its limited bandwidth resources to meet the stringent demands of a highly dynamic and safety-critical vehicular environment.

Section 2: The IEEE 802.15.7 Standard: A Foundation for V-OCC

2.1 Overview of the IEEE 802.15.7 MAC Protocol

The IEEE 802.15.7 standard provides the foundational framework for VLC and OCC systems, defining the necessary PHY and MAC layer specifications for establishing an optical wireless personal area network (OWPAN or VPAN).[4] This standard is the starting point from which the Optimized DynaVLC algorithm builds and innovates. It supports multiple network topologies, including peer-to-peer, star, and broadcast, which are all relevant to the V2V and V2I scenarios in vehicular networking.[2]

Central to the MAC layer's operation is the superframe structure, which organizes channel time to facilitate both contention-based and scheduled access. The superframe is bounded by beacons sent by a network coordinator (e.g., a roadside unit or a lead vehicle) and is divided into three primary parts [15]:

1. **Beacon:** A synchronization frame transmitted at the beginning of each superframe. It contains network information, timing parameters, and slot allocation details.
2. **Contention Access Period (CAP):** A portion of the superframe where devices compete for channel access using a Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism. This period is suitable for non-periodic, low-latency data or for devices to request dedicated transmission slots.[17]
3. **Contention-Free Period (CFP):** A portion of the superframe that consists of a series of Guaranteed Time Slots (GTS). These slots are pre-allocated by the coordinator to specific devices, ensuring collision-free data transmission. The CFP is ideal for periodic, high-priority, or latency-sensitive data streams, which are common in vehicular safety applications.[15]

2.2 Key MAC Parameters and Their Function

The behavior of the IEEE 802.15.7 superframe is governed by a set of key parameters that are configured by the network coordinator. The DynaVLC algorithm achieves its adaptability by dynamically manipulating these very parameters. The most important ones include:

- **Beacon Order (BO) and Superframe Order (SO):** These two integer values are exponents that determine network timing. The Beacon Interval (BI), which is the time between consecutive beacons, is calculated based on BO. The Superframe Duration (SD), which is the length of the active portion of the superframe, is calculated based on SO. The relationship is defined as SD=aBaseSuperframeDuration×2SO, where aBaseSuperframeDuration is a constant. The standard mandates that $0 \leq SO \leq BO \leq 14$, ensuring the active superframe is never longer than the beacon interval.[2]
- **CSMA/CA Parameters:** During the CAP, the channel access mechanism is controlled by several variables for each device:
  - **Number of Backoffs (NB):** The number of times the CSMA/CA algorithm was required to back off while attempting to access the channel.
  - **Backoff Exponent (BE):** This value determines the range from which a random backoff period is chosen.
  - Contention Window (CW): This parameter defines the number of backoff slots that must be clear before a device can transmit.
    The standard allows for service differentiation by assigning different initial values for these parameters to different priority levels.16

2.3 The Rigidity of the Standard and the Opportunity for Optimization

While the IEEE 802.15.7 standard provides a comprehensive and robust framework, its design is inherently semi-static. It was originally conceived for general-purpose Wireless Personal Area Networks (WPANs), which typically feature far less mobility and topological volatility than a vehicular network.[15] In a standard implementation, parameters like

BO and SO are configured for the network and are not intended to change on a moment-to-moment basis in response to fluctuating conditions. This rigidity creates a significant performance gap when the standard is applied directly to the chaotic environment of V-OCC.

The core issue is that a single, fixed configuration cannot be optimal for the wide range of scenarios encountered on the road. For example, a dense traffic jam is characterized by high node density and low mobility, a situation that demands a large number of GTS slots (a long CFP) to serve many vehicles with periodic updates. Conversely, open highway driving involves low node density and high mobility, where a large, pre-allocated CFP would be wasteful, and a more flexible, contention-based approach might be more efficient. A static MAC configuration optimized for one scenario will perform poorly in the other.

This is the opportunity the Optimized DynaVLC algorithm seizes. It recognizes that the parameters defined by the standard are powerful levers for controlling network behavior. The fundamental innovation of the project is the introduction of a real-time feedback loop that connects live network metrics—namely, vehicle density and speed—to these control levers. By continuously measuring the state of the vehicular environment and using that data to retune the MO, SO, and CAP/CFP balance, the algorithm transforms the static IEEE 802.15.7 framework into a dynamic, adaptive system. It is purpose-built to handle the specific and extreme variability of vehicular communication, thereby bridging the performance gap left by the standard's inherent rigidity.

Section 3: The Optimized DynaVLC Algorithm: Design and Mechanics

3.1 Core Concepts and Heuristics

The Optimized DynaVLC algorithm is built upon a set of clear, pragmatic concepts and heuristics designed to translate real-world vehicular conditions into concrete MAC parameter adjustments. These foundational elements allow the algorithm to make intelligent, real-time decisions about resource allocation.[14]

- OCC Eligibility Condition: The algorithm first establishes a practical rule to determine which vehicles can participate in the OCC network at any given time. A vehicle is considered eligible only if it meets specific environmental and

operational criteria:
$\text{Eligible}(v)=(W\in\{\text{Clear, Night}\})\land(10\le \text{speed}\le 35)$
This condition ensures that communication is attempted only when it is most likely to succeed, filtering out adverse weather conditions and speeds that are too low (implying a stopped vehicle) or too high for reliable OCC link establishment with the given parameters.14

- **Key Operational Metrics:** The algorithm's decision-making process is driven by three primary real-time metrics:
  1. **Number of OCC-eligible vehicles (VOCC):** This serves as the direct input for assessing network density and immediate demand for communication resources.
  2. **Average vehicle speed (α):** This metric is used to gauge the level of mobility and topological volatility in the network.
  3. Pressure Ratio (ρ): This is the central and most elegant heuristic of the algorithm. It provides an instantaneous, normalized measure of network congestion by comparing the required resources to the available resources. It is calculated as:

     ρ=NCFPR

     where R is the number of required GTS slots (equal to ∣VOCC∣) and NCFP is the total number of available GTS slots in the current configuration. A value of ρ>1 signifies that demand exceeds supply, while ρ<1 indicates surplus capacity.14

3.2 Dynamic Parameter Control: An Annotated Code Analysis

The logic of the DynaVLC algorithm is executed within a loop for each beacon interval, ensuring continuous adaptation. The process can be deconstructed into the following logical steps, presented here as annotated code snippets for clarity.[14]

Snippet A: Real-time Network Sensing and Resource Calculation

```C
// For each beacon interval:
Measure traffic V, compute VOCC;
Compute R = |VOCC|;
Compute NCFP = C * (CFPbase + MO);
Compute ρ = R / NCFP;
Compute average vehicle speed α;
```

- **Explanation:** This initial block functions as the algorithm's sensory input. At the beginning of every beacon interval, it assesses the environment. It measures the total number of vehicles (V) within communication range and applies the eligibility condition to determine the count of active participants (VOCC). This count directly translates to the number of required GTS slots (R). Simultaneously, it calculates the currently available GTS slots (NCFP) based on the number of channels (C), a base slot count (CFPbase), and the current Multi-superframe Order (MO). From these two values, it computes the critical Pressure Ratio (ρ). Finally, it calculates the average vehicle speed (α), providing the necessary inputs for all subsequent adaptation logic.[14]

Snippet B: Load-Aware Adjustment of Multi-Superframe Order (MO)

```C
if (ρ > 1.0) {
  MO = MO + 1;
} else if (ρ < 0.5 && MO > 0) {
  MO = MO - 1;
}
MO = min(MO, BO); // Enforce constraint
```

- **Explanation:** This logic directly addresses network congestion using the pressure ratio. If ρ exceeds 1.0, it signifies that there are more vehicles needing a guaranteed slot than are available. In response, the algorithm increments the MO, effectively adding more superframes to the beacon interval, thereby increasing the total pool of available GTS slots. Conversely, if the network is significantly underutilized (ρ < 0.5), the algorithm decrements MO (provided it is not already zero) to shrink the superframe structure, reducing overhead and potential latency. The final min(MO, BO) command is a crucial safeguard that ensures the multi-superframe structure remains valid within the bounds of the overall beacon interval as defined by the Beacon Order (BO).[14]

Snippet C: Mobility-Aware Adjustment of Superframe Order (SO)

C

```c
if (α > 25 && SO < BO) {
  SO = SO + 1;
} else if (α < 15 && SO > 0) {
  SO = SO - 1;
}
```

- **Explanation:** This component adapts the fundamental timing of the superframe to the physical speed of the vehicles. When the average speed α is high (greater than 25 units), SO is increased. Since the Superframe Duration (SD) is proportional to 2SO, this results in a *longer* active superframe. This counter-intuitive step provides a larger, more stable time window for communication, which is beneficial for completing transmissions and handshakes with fast-moving vehicles before they travel out of range. When traffic is slow (α < 15), SO is decreased, creating shorter, more agile superframes. This is more efficient for the frequent, bursty updates that might be needed in dense, slow-moving traffic, reducing idle channel time.[14]

Snippet D: Dynamic Contention Access Period (CAP) Reduction Logic

```C
if (ρ > 0.7) {
   Enable CAP_Reduction;
} else if (ρ < 0.3) {
   Disable CAP_Reduction;
}
```

- **Explanation:** This is a powerful optimization that reallocates channel time based on demand. When network load becomes high ($\rho > 0.7$), the algorithm enables CAP reduction. This mechanism reclaims the time that would normally be reserved for the contention-based CAP and converts it into additional collision-free GTS slots. This prioritizes guaranteed, reliable communication when the network is busy. When the load is very low ($\rho < 0.3$), the feature is disabled, restoring the CAP to allow for more flexible, non-scheduled transmissions when there is ample bandwidth to spare.[14]

3.3 The Adaptive Superframe Architecture

The practical effect of the CAP reduction logic is best understood visually. The algorithm transforms the static superframe defined by the standard into a dynamic, elastic structure. When CAP reduction is enabled, the time allocated for contention-based access is systematically repurposed to expand the contention-free period.

The figure provided in the source material, "Multi-superframe structure with CAP reduction enabled," illustrates this concept perfectly.[14] In a standard multi-superframe, each superframe would have its own CAP and CFP. However, with CAP reduction active, the algorithm can effectively eliminate the CAP from subsequent superframes within the multi-superframe block, dedicating that entire duration to additional GTS slots. This creates a large, contiguous block of guaranteed transmission opportunities, maximizing channel utilization for scheduled traffic precisely when the network load is highest.

3.4 A Dual-Axis Optimization Strategy

The Optimized DynaVLC algorithm design demonstrates a particularly sophisticated approach to adaptation. Instead of relying on a single metric to control all parameters, it employs a dual-axis optimization strategy that decouples the management of network capacity from the management of network volatility.

The first axis is **capacity management**. This is driven by vehicle density, which is captured by the Vocc metric and abstracted into the Pressure Ratio (ρ). This ratio governs the *quantity* of available communication resources by controlling the Multi-superframe Order (MO) and the state of CAP reduction. It fundamentally answers the question: "How many communication slots do we need right now?"

The second axis is **volatility management**. This is driven by vehicle mobility, captured by the average vehicle speed (α). This metric governs the *timing and duration* of the communication cycle by controlling the Superframe Order (SO). It answers a different question: "What is the optimal duration for our communication cycles to ensure reliable links, given how fast the network topology is changing?"

This separation of concerns is a hallmark of an advanced control system. A simpler algorithm might attempt to use a single, composite metric to adjust all parameters, but this could lead to suboptimal outcomes. For instance, a traffic jam (high density, low speed) and a multi-lane highway race (high density, high speed) might have similar density values but require vastly different superframe timings. By using two independent inputs to control two different aspects of the MAC structure, the DynaVLC algorithm can adapt more precisely and effectively to a wider and more complex range of real-world vehicular scenarios.

Section 4: Performance Analysis and Comparative Evaluation

The effectiveness of the Optimized DynaVLC algorithm is not merely theoretical; it has been validated through comparative simulations against the baseline IEEE 802.15.7 standard. The results, presented in terms of network throughput and maximum delay, demonstrate substantial performance gains, particularly under high network load.

4.1 Analysis of Network Throughput

Figure 1 in the project documentation compares the normalized network throughput of the Optimized DynaVLC algorithm against the baseline standard as a function of the number of active GTS transmissions.[14] Throughput is a measure of the rate of successful data delivery over the communication channel.

Graph analysis reveals a clear and consistent advantage for the optimized algorithm. While both systems perform similarly at very low loads (around 20 GTS transmissions), a performance gap emerges and widens as the network becomes more congested. For instance, at a load of 100 GTS transmissions, the baseline IEEE 802.15.7 protocol achieves a normalized throughput of approximately 0.65. In contrast, the Optimized DynaVLC algorithm sustains a throughput of roughly 0.75 under the same conditions. This represents a relative improvement of over 15% in data delivery efficiency.

This superior performance can be directly attributed to the algorithm's adaptive mechanics. As the number of vehicles requiring a GTS slot increases, the pressure ratio ρ increases. This triggers the algorithm to increase the MO and enable CAP reduction, dynamically creating more GTS slots to accommodate the demand. By providing more opportunities for collision-free transmission, the algorithm minimizes packet loss that would otherwise occur from contention or insufficient resources, thereby directly boosting the overall network throughput.

4.2 Analysis of Maximum Delay

Figure 2 presents a comparison of the maximum communication delay, measured in optical clocks.[14] For vehicular networks, particularly those supporting safety-critical applications, latency is arguably a more important metric than throughput. A message warning of a sudden stop must arrive almost instantaneously to be useful.

In this domain, the performance of the Optimized DynaVLC algorithm is even more compelling. The graph shows that the baseline system's maximum delay increases sharply with network load. At 80 GTS transmissions, the baseline system's delay already reaches 140 optical clocks. In stark contrast, the delay for the Optimized DynaVLC algorithm remains remarkably low and stable, hovering around 70 optical clocks at the same load. This constitutes a 50% reduction in maximum delay.

This dramatic improvement highlights the effectiveness of proactively managing resources. The baseline system, with its static resource allocation, forces more devices to compete for limited slots as load increases, leading to queuing delays and retransmission attempts that cause latency to skyrocket. The DynaVLC algorithm, by dynamically expanding the pool of guaranteed slots to match the demand, ensures that vehicles can transmit their data promptly and predictably. This ability to maintain low and stable latency, even under significant network stress, is the algorithm's most critical contribution to enabling reliable and safe vehicular communication.

4.3 Quantitative Performance Summary

To provide a clear, at-a-glance summary of the performance evaluation, the graphical data can be distilled into a comparative table. This table quantifies the advantages of the Optimized DynaVLC algorithm across different network load conditions.

Table 1: Comparative Performance Metrics: Optimized DynaVLC vs. Baseline IEEE 802.15.7

Network Load (GTS Transmissions)	Metric	Baseline IEEE 802.15.7	Optimized DynaVLC	Performance Gain
Low (40)	Throughput (Norm.)	~0.58	~0.65	**+12%**
Low (40)	Max Delay (Clocks)	~110	~65	**-41%**
Medium (80)	Throughput (Norm.)	~0.63	~0.73	**+16%**

Medium (80)	Max Delay (Clocks)	~140	~70	**-50%**
High (120)	Throughput (Norm.)	~0.68	~0.78	**+15%**
High (120)	Max Delay (Clocks)	~155+	~75	**-52%**

This quantitative summary powerfully reinforces the findings from the graphical analysis. It shows that the Optimized DynaVLC algorithm consistently outperforms the baseline standard across all tested scenarios. More importantly, it demonstrates that the performance benefits, especially in terms of delay reduction, become more pronounced as the network becomes more stressed. This robust performance under pressure is a key indicator of a well-designed protocol suitable for the unpredictable nature of real-world traffic.

Section 5: Conclusion: Significance and Future Impact

5.1 Summary of Contributions

This project has successfully designed, detailed, and validated an **Optimized DynaVLC algorithm** tailored specifically for the unique demands of vehicular networks operating exclusively with Optical Camera Communication (OCC).[14] The core contribution of this work is the development of an intelligent and highly adaptive MAC protocol that moves beyond the static nature of the baseline IEEE 802.15.7 standard. By creating a real-time feedback loop, the algorithm dynamically adjusts key MAC parameters—namely the Multi-superframe Order (MO), Superframe Order (SO), and the allocation of channel time via CAP reduction—based on continuous measurements of vehicular density and speed.[14] This transforms the rigid standard into a flexible, living system capable of optimizing its own performance in a constantly changing environment.

5.2 Proven Effectiveness

The effectiveness of the proposed algorithm is not speculative but has been clearly demonstrated through rigorous performance analysis. The comparative simulations show that the Optimized DynaVLC algorithm yields substantial and measurable benefits over the standard IEEE 802.15.7 implementation. These benefits include a significant increase in network throughput, with performance gains of up to 16%, indicating more efficient use of the limited OCC bandwidth. Most critically, the algorithm achieves a dramatic reduction in maximum communication delay, cutting latency by over 50% under moderate to high network loads.[14] This ability to ensure low and predictable latency is a fundamental prerequisite for deploying the safety-critical applications that represent the primary motivation for vehicular communication systems.

5.3 Broader Impact on Vehicular Communication

The implications of this work extend beyond academic performance metrics. By engineering a solution that makes V-OCC significantly more efficient, reliable, and responsive, this project represents a practical and important step toward realizing the full potential of optical wireless technology in the automotive sector. The algorithm addresses the primary bottleneck of V-OCC—inefficient management of its low-bandwidth channel—and in doing so, makes it a more viable candidate for supporting applications that enhance vehicle safety, improve traffic flow management, and enable the rich inter-vehicle connectivity of the future. Furthermore, the algorithm's pragmatic design, which builds upon an existing industry standard and leverages the capabilities of commercial off-the-shelf (COTS) hardware like LEDs and cameras, positions it as a feasible engineering solution that could be integrated into near-term vehicular systems.[6] This work thus contributes not only a novel algorithm but also a foundational piece of the technological puzzle required to build the safer, smarter, and more connected transportation systems of tomorrow.

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