Renovating Road Signs for Infrastructure-to-Vehicle Networking

A Visible Light Backscatter Communication and Networking Approach

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ABSTRACT

Conventional road signs convey very concise and static visual information to human drivers, and bear retroreflective coating for better visibility at night. This paper introduces RetroI2V – a novel infrastructure-to-vehicle (I2V) communication and networking system that renovates conventional road signs to convey additional and dynamic information to vehicles while keeping intact their original functionality. In particular, RetroI2V exploits the retroreflective coating of road signs and establishes visible light backscattering communication (VLBC), and further coordinates multiple concurrent VLBC sessions among road signs and approaching vehicles. RetroI2V features a suite of novel VLBC designs including late-polarization, complementary optical signaling and polarization-based differential reception which are crucial to avoid flickering and achieve long VLBC range, as well as a decentralized MAC protocol that make practical multiple access in highly mobile and transient I2V settings. Experimental results from our prototyped system show that RetroI2V supports up to 101 m communication range and efficient multiple access at scale.

CCS CONCEPTS

• **Hardware** → **Wireless devices**; • **Computer systems organization** → *Embedded systems.*

KEYWORDS

Visible Light Backscatter Communication; Infrastructure-to-Vehicle Networking; Polarization-based differential reception

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1 INTRODUCTION

As automotive industry is investing heavily and innovating constantly on autonomous vehicles, we argue that it is equally important to invest on the road infrastructure and make the road more intelligent to sense dynamic road and traffic conditions such as accidents, road work, water or icy surfaces. Such conditions may be difficult for a vehicle's onboard sensors (*e.g.,* cameras and LiDAR) to recognize and reason about. In fact, there are growing efforts in instrumenting smart sensors to the road infrastructure as part of the infrastructure modernization progression across the world [1–7]. Infrastructure-to-vehicle (I2V) communication and networking means are required to *convey* road sensory data to oncoming vehicles. Dedicated short-range communications (DSRC) is the only widely recognized mature technology so far. However, its high cost (*e.g.,* hundreds or even thousands of dollars per RSU [8]), external power requirement, necessity of Internet backhaul connectivity and dependency on DSRC-capable vehicles' relay for extended coverage, have prevented its deployment at scale. *Cheap, gradually and easily deployable* solutions are highly desired.

On the other hand, road signs, and traffic signs in particular, are installed here and there, at every spot that needs one. It is beyond question that traffic signs are of critical importance to driving safety and traffic management. Traffic signs are essentially designed for clear human visual perception by using highly contrasting colors for foreground content and the background, and retroreflective adhesive plastic coatings for nighttime and low-light visibility. New generations of traffic signs based on electronic displays (mostly large LED arrays) for dynamic content display are increasingly deployed. Unfortunately, all of today's traffic signs are *not friendly* to the camera-based vision system of autonomous vehicles. Their cameras are usually of wide field of view, limited dynamic range, as compared to the human vision system. They tend to focus on nearby large objects and perform average exposure for the whole view. As a result, faraway traffic signs always appear small, out-of-focus, and over-exposure at nighttime and low-light conditions. Subsequent advanced AI-based vision processing would likely fail to extract any useful information carried by the traffic signs. When the traffic signs become close enough, the vision system may do the job but it is already too late to react accordingly.

A question naturally arises: can we renovate the traffic signs and make them communicate with vehicles while retaining its very original purpose – convey information to humans? Inspired by previous work on visible light backscatter communication (VLBC) [9], in this paper, we provide an affirmative answer to the question through the design of RetroI2V. We envision renovating a road sign (termed RetroSign hereafter) by covering a certain portion of its retroreflective coating with tiles of transparent LCDs, and appending a tiny control circuitry and a small solar panel. The size and the content of the road signs remain unaltered. When interrogated by an oncoming RetroI2V-capable vehicle (*i.e.,* equipped with a Reader that consists of a headlight, light sensor and circuitry board), the RetroSign can convey information to vehicles via VLBC.

The retroreflecting trait of RetroSign makes the communication to a Reader reactive and highly directional, hence minimizes interference among Readers. This differentiates RetroI2V from other potential alternative radio backscattering based solutions such as RFID [10] and bistatic backscatter [11–19] whose omnidirectional backscattering introduces large interference range and even interferes with those on the opposite side of the road. As a remark, a RetroI2V-capable vehicle can immediately benefit from any renovated road sign, without any dependency on other vehicles or infrastructure. Thus, our RetroI2V solution is indeed *gradually deployable*. By virtue of backscattering, a RetroSign requires *no* external power source and is thus directly applicable to existing traffic sign infrastructure. This would greatly simplify the actual deployment. Our solution is also cheap. The BOM cost of our experimental RetroSign is only about $38 and that of add-on circuitry of the Reader is about $70.

To be a pragmatic I2V solution, the following requirements, in addition to the aforementioned cost and deployability, must be met: *i) flicker-free* – avoid annoyance to human drivers as human vision system is very sensitive to motion and flickers; and *ii) long communication range* – tens, if not hundreds, of meters – is critical, for the sake of enough space and time to take actions when necessary; *iii) multiple access* – effectively communicate even when multiple RetroSigns exist in the view of a plural of Readers. While previous works [9, 20] demonstrated feasibility of VLBC for certain short range (a few meters) IoT settings, their schemes *cannot* fulfill these requirements. Flicker is doomed due to the on-off keying (OOK) nature of all previous VLBC schemes. It becomes more severe when OOK at a relatively lower frequency, which is a non-choice if to extend the communication range. The retroreflected signal attenuates at the power of fourth order with increasing distances. It is hard to achieve long communication range by simply increasing the power of the Reader or the size of the reflective surface of the RetroSign, putting aside the much adverser lighting environment. Readers come and go randomly, and RetroSigns can be temporarily deployed. Readers cannot know in advance if other Readers or RetroSigns are nearby, nor do RetroSigns. Sharp directionality of VLBC leads to severe hidden terminal problem when there are multiple Readers and RetroSigns in communication range. Collisions will result when multiple Readers talk to the same RetroSign simultaneously or multiple RetroSigns are interrogated by the same Reader. These factors make multiple access extremely challenging.

RetroI2V conquers these challenges and fulfills the three requirements through physical layer (both front-end and demodulation) innovations and a completely new MAC layer design. Realizing the fundamental requirement of VLBC being that two polarizers sandwiching a liquid crystal need to be in the reflecting path, inspired by the recent design in traditional (active) visible light communication [21, 22], we detach the front polarizer from a normal LCD shutter and move it all the way to the receiving light sensor on the Reader. This *late-polarizing* design solves the flickering issue (§4.1). To tackle the long communication range challenge, we design a new *complementary optical signaling* front-end by forming a pair of receiving units (*i.e.,* a light sensor with a covering polarizer) with orthogonal polarities. We further develop a *polarization-based differential reception* (PDR) scheme that subtracts the signals from the two receiving units and extracts information thereof. The new front-end and PDR not only boost the received signal strength, but also suppress all common-mode noises at the same time. As a result, SNR is significantly improved and long range communication becomes achievable (§4.2). Our experiment achieves 5.3 dB SNR improvement over the baseline.

We conduct thorough analysis on possible collision cases and design a *decentralized multiple access* MAC layer protocol. We propose excitatory carrier sensing and a random backoff mechanism to handle downlink (*i.e.,* Reader to RetroSign) collision. To solve the uplink (*i.e.,* RetroSign to Reader) collision which may happen synchronously or asynchronously, we design a reactive, on-the-fly *Virtual ID* assignment scheme and achieve unicast capability for the complicated multiple access situations (§5).

We have prototyped RetroI2V (§6) to demonstrate its practicality for real-world applications. Our Reader design can be organically integrated into today's LED-based vehicular headlight complying with its power regulation. We benchmarked our system under different network sizes, data rate, relative location and orientation, and ambient lighting conditions including different weather and sunlight incidence. Experimental results show that RetroI2V-enabled host vehicles can talk to a RetroSign at the distance of up to 101 m and our multiple access solution scales in typical I2V settings (§7).

To sum up, we design, implement and demonstrate the feasibility of RetroI2V, the first retroreflective I2V communication and networking system that renovates road signs to deliver dynamic information to host vehicles. RetroI2V's design makes three key technical contributions, namely late-polarizing and complementary optical signaling front-end design, a polarization-based differential reception PHY scheme and a decentralized and efficient multiple access MAC protocol.

2 BACKGROUND

2.1 Motivating Use Cases

In this work, we seek to renovate existing static road signs and make them capable of delivering dynamic information. The critical locations of existing road signs make them ideal candidates to disseminate highly local road dynamics that are intrinsically location-bound, especially in those places where Mobile Internet service (*e.g.,* Google maps) and/or RF-based LPWAN technology (*e.g.,* NB-IoT, LoRa, and Sigfox) are either unavailable or unreliable such as urban canyon and remote area in general. We categorize several potential use cases either missing from status quo or no easy solutions for deployment at scale.

Additional Information. When an accident happens on the road, an emergency warning triangle sign is required to be placed so that upcoming vehicles can take proper action. However, current emergency signs can only be of warning function. If additional information such as if help is needed, or the emergency is caused by a flat tire or engine problem *etc.* is provided, other drivers may better justify the situation and offer an early hand.

Time Limited Road Restrictions. Many traffic signs append additional restriction or validation time, often specified in smaller fonts. For instance, a school zone sign may indicate its effective time duration, and a left-turn forbidden sign may dismiss the restriction after a certain time. If the vehicle can be informed automatically by talking to the road signs, it can warn the driver accordingly in case the driver fails to see the restrictions and misbehaves. As yet another example, certain informative signs may wish to provide a hyperlink to more detailed information pages on the web. A vehicle can automatically retrieve the content and show on its display.

Spot Weather Impact Warning. Static speed limit signs generally provide a safe speed limit based on the road geometry (straight or curved) and normal road surface conditions. However, the road surface is directly affected by the weather conditions. For example, a wet or icy road surface may have significantly lower friction. The actual safe speed limit should be adjusted and posted accordingly. With input from temperature and humidity sensors, the dynamically refined safe speed limit can be regressed. If such information is timely conveyed to the vehicle (for driver), when the driving speed exceeds the actual safe limit (but still within the limit shown in the static sign), the vehicle can warn the driver to slow down.

2.2 VLBC Primer

The state-of-the-art visible light backscattering communication (VLBC) schemes [9] exploit retroreflection fabric to pinpoint the reflected light back to the interrogating reader and toggle on/off states of an LCD shutter to modulate the reflected light carrier via on-off keying (OOK). A VLBC system consists of a high power reader and a low power tag. It works as follows: the LED in the reader switches on and off (at a frequency high enough to avoid human-perceivable flicker), turning the illuminating light into a communication carrier. Information bits are carried using a certain modulation method. The light signals are picked up by the light sensor on the tag and decoded therein. For the uplink, the same carrier is leveraged via reflection. The tag remodulates the retroreflected light and sends information bits via OOK, which is achieved with an MCU-controlled LCD shutter atop the reflecting fabric. The (re-)modulated reflected light carrier is then picked up by a photodiode on the reader and further demodulated and decoded.

3 RETROI2V OVERVIEW

3.1 Requirements and Challenges

Status-quo designs [9, 20, 23] have demonstrated the feasibility of VLBC and its short range IoT applications, it is non-trivial to apply those designs to our target I2V scenarios which have the following specific requirements and challenges.

Flicker-free. Human vision system (especially the peripheral vision) is very sensitive to motion and flicker. Flickering road signs can easily distract a driver and may result in dizziness and headaches [24], hence must be avoided.

• *Challenge:* Flicker is inevitable due to the on-off keying (OOK) nature of all previous VLBC schemes. It becomes more severe when OOK is performed at a lower frequency, which is a non-choice if to extend the communication range. Our measurements show the toggle rate is 125 Hz and the flickering effect is perceivable due to the Phantom effect of human vision system [25].

Long Communication Range. Tens, if not hundreds, of meters communication range is critical, for the sake of enough space and time to take actions when necessary. Considering a vehicle traveling

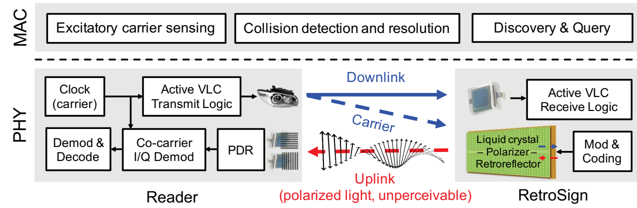


Figure 1: RetroI2V system architecture.

at a legal speed of 75 mph on a local highway and encountering an emergency RetroSign, a simple kinematics analysis[1] shows the host vehicle should be able to communicate with the RetroSign at least 76.1 m ahead to avoid crashes.

• *Challenge:* The link budget model [9] indicates an exponentially decaying path loss model, at a power of fourth order. Thus, simply increasing the power of Reader or the size of reflective surface of the RetroSign is not an option to extend communication range – the headlight power can't be increased further for eye safety regulations. Moreover, in I2V situations, a retro-communication path may suffer from strong self-interference (*i.e.,* reflections from unintended retroreflectors), ambient lights, vehicles beams from the opposite direction, and other dynamic multipath reflections by the ground. High power LED drive circuits also introduce severe electronic noises to a Reader's receiving circuitry.

Multiple access. In some cases, multiple RetroSigns may coexist in the common view of a plural of Readers. RetroI2V should guarantee all the in-view RetroSigns can communicate with each host vehicle during the encountering period.

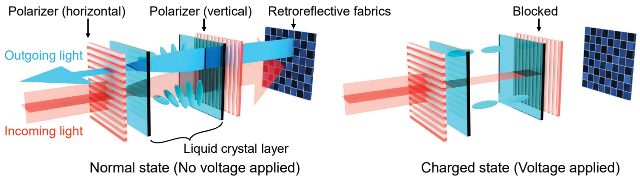
• *Challenge:* Collisions are doomed when multiple Readers talk to the same RetroSign simultaneously or a plural of RetroSigns are interrogated by the same Reader. Unfortunately, there is no coordination between RetroSigns. RetroSigns cannot sense the existence of other RetroSigns in its proximity either. Readers come and go randomly and cannot possibly know in advance if other Readers or RetroSigns are within its communication range.

3.2 System Overview

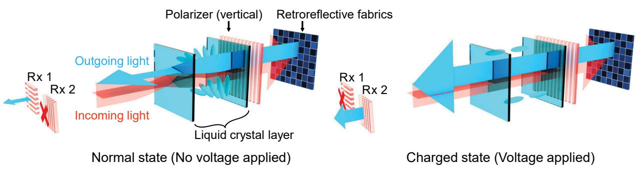
While still belonging to a type of VLBC in principle, *i.e.,* modulated passband LED light carrier for downlink (Reader to RetroSign) and LCD re-modulated retroreflected light carrier for uplink (RetroSign to Reader) communications, we have come up with a completely new design of RetroI2V to meet the aforementioned I2V requirements. The high-level design of RetroI2V is illustrated in Fig. 1. The system consists of two layers, namely PHY and MAC layer. We provide an overview of the new design in this section and elaborate design details in subsequent sections.

PHY. The redesign of RetroI2V PHY features three innovations. Firstly, a new front-end design. The front polarizer of the LCD is moved from the RetroSign to the Reader, in front of its receiving light sensor. This *late-polarizing* design completely avoids flickering (§4.1). *Complementary optical signaling* is achieved with a pair of light sensors covered with polarizers in orthogonal polarities.

[1]The vehicle in emergency should first query RetroSign and then decelerate to full stop, breaking the safety distance into: $D = D_{sen} + D_{decel} = vt_{sen} + \frac{v^2}{2\mu g} = 76.1$ m, where we have $t_{sen} = 59.2$ ms with 7-byte downlink query at 5 Kbps and 6-byte uplink response at 1 Kbps, $\mu = 0.9$ [26] and $v = 130$ km/h (considering 8% speeding).



(a) Normal LCD and its states in other VLBC schemes.



(b) Modified LCD and its states in RetroI2V.

Figure 2: Structure and effect comparison of RetroI2V and other VLBC schemes. Notice the difference in the locations of the front polarizer layer.

Secondly, a *polarization-based differential reception* scheme. The received signals from this pair of receiving units are subtracted (§4.2). This not only helps to suppress self-interference, common-mode optical and electronic noise, but also doubles received signal strength. The differential signals are demodulated and decoded with an I/Q demodulator using the local generated carrier. Thirdly, *excitatory carrier sensing* (ECS). When not in an active communication session (including transmission and backoff), the Reader continuously emit a carrier at f_u, which is different from that used for active downlink transmission at f_d. This is to avoid the in-band interference from downlink reflection while receiving the (reflective) uplink data in the multiple access scenario.

MAC. We conduct a thorough analysis on possible collision cases and design a *decentralized multiple access* MAC layer protocol. It has two communication primitives: *discovery* and *query*. A Reader initiates, discovers and communicates with all the RetroSigns. Downlink collisions are handled via random backoff. ECS is used mitigate the chances of synchronous uplink collisions. Overhearing, a side effect of ECS, is leveraged to suppress possible repeated queries among collocated Readers. Synchronous uplink collisions are addressed through a reactive *virtual ID* addressing mechanism. Several optimizations are made to boost MAC efficiency. All these design and measures enable a Reader to discover and communicate with all RetroSigns via unicasts (§5).

4 RETROI2V PHY LAYER

We present the PHY design of RetroI2V to meet the requirements of flicker-free and long-range operation.

4.1 The Front-end Design

The design of VLBC in all previous arts exploited the LCD shutter, which passes or blocks reflected light through controlling the states of the LCD. The fundamental structure of a LCD consists of two polarizers sandwiching a liquid crystal (LC) layer. As shown in Fig. 2a, the key enabler is the polarity changing property of LC under different voltages. We realize that the two polarizers and the LC layer do not need to be collocated. Rather, as long as they are present, and in the correct order (*i.e.,* LC layer has to be in-between of two polarizers), in the light communication path, they will function normally. On the other hand, human eyes cannot perceive the polarization of light. These thoughts give rises to the new front-end design of RetroI2V.

Late Polarization. Concretely, we separate the two polarizers collocated with the LC layer in a normal LCD, and move the front polarizer from the LCD all the way to the front of a receiving light sensor on the Reader, as shown in Fig. 2b. From the figure, we see that in view of a receiving light sensor, the light is still either passed or blocked at alternate states of LC layer as in all other VLBC schemes. But in sharp comparison, in RetroI2V, regardless of the states of the LC layer, there is always light being (retro-)reflected. The exiting reflected light from the modified LCD of RetroSign is always polarized, its polarity is determined by the LC charging state. As human eyes can perceive light intensity but not its polarity, and lights in different polarities are of the same intensity, therefore no flicker will ever appear. The second polarization is postponed till the reflecting light hits the reader, hence the name *late-polarization*.

Complementary Optical Signaling. Inspired by the concept of differential signaling (*i.e.,* transmitting information using two complementary signals) that is widely applied and proven effective in circuit design (*e.g.,* USB and Ethernet) to reduce common mode electromagnetic interference and noises, we add a new set of light sensors and further cover the two set of light sensors with two polarizers with orthogonal polarities (*e.g.,* one horizontal and one vertical). This results in paired receiving units, shown as Rx_1 and Rx_2 in Fig. 2b, which helps to increase the received signal energy. Note that the addition of two polarizers effectively turn one input light signal into two polarity-complementary light signals, hence enables *complementary optical signaling*.

4.2 Polarization-based Differential Reception

When the LC changes its state from charging to discharging and vice versa, the polarity of outgoing light beam changes accordingly. This enables RetroSign to modulate information bits with different polarization states, *e.g.,* by mapping "1" and "0" to horizontally and vertically polarized outgoing light, by changing the voltage applied on the LC. This binary polarization shift keying modulation scheme, together with complementary optical signaling, enables the *polarization-based differential reception* (PDR) design.

According to Malus's law, when polarized light incidents squarely[2] on a polarizer, then the intensity I_θ of passed-through light is determined by the effective intensity I_0 of the incident light and the bearing angle θ between the polarity of incident light and the polarizing direction of the polarizer: $I_\theta = I_0 cos^2(\theta)$. Note that the overall system noises ($\sigma(t)$) consist of relatively stronger self-interference (*i.e.,* reflections caused by unintended retroreflectors), ambient lights and vehicles beams from the opposite direction, and other dynamic multipath reflections by the ground and other on-road objects. Since these noises are unpolarized, their intensity will be attenuated by half after passing the polarizer at the receiving units at Reader. Therefore, for the two collocated receiving units, we have:

$$I_{Rx_1}(t) = I_{\theta_1}(t) + \sigma_1(t)/2$$
$$I_{Rx_2}(t) = I_{\theta_2}(t) + \sigma_2(t)/2$$

[2]If the light incidents at an angle α, then the effective intensity is scaled by $cos(\alpha)$, but Malus's law regarding polarization always holds.

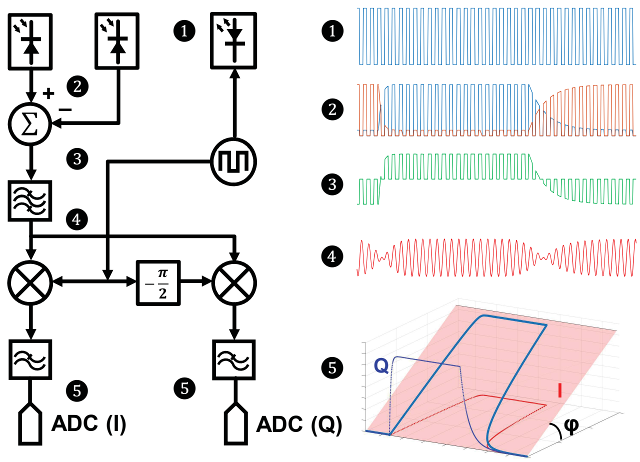


Figure 3: Receiver signal processing flow at Reader and the corresponding waveforms at different stages. ❶ Excitatory carrier signals, also used for homodyne detection; ❷ Complementary signals at differential optical signaling front-end; ❸ PDR output with noise suppression; ❹ Bandpass filtered signals for homodyne detection; and ❺ Final reconstructed I/Q samples for symbol decision and decoding.

where I_{θ_1} and I_{θ_2} are the received light intensity at the two light sensors at the Reader, and can be expressed as $I_0 cos^2(\theta_1)$ and $I_0 cos^2(\theta_2)$ regarding polarization bearing angle.

The complementary optical signaling front-end ensures $\theta_1 + \theta_2 = 90\,^\circ$. When the LC is charged (from state "0" to "1"), θ_1 is changing from $0\,^\circ$ to $90\,^\circ$, and θ_2 is changing from $90\,^\circ$ to $0\,^\circ$. Consequently, I_{θ_1} and I_{θ_2} are complementary. When one is falling, the other will be rising. We have $\sigma_1(t) \approx \sigma_2(t)$ because they are essentially the self-inflicted reflection from ambient on-road objects experiencing same path(s) and thus are not polarized before passing the polarizer filter. Taking differences between inputs of the two receiving units leads to the *polarization-based differential reception* (PDR) scheme.

$$I_{Rx_1}(t) - I_{Rx_2}(t) = I_{\theta_1}(t) - I_{\theta_2}(t) + (\sigma_1(t)/2 - \sigma_2(t)/2)$$
$$I_{Rx_1}(t) - I_{Rx_2}(t) \approx I_0(2cos^2\theta_1(t) - 1) = 2I_{\theta_1}(t) - constant$$

Clearly, with PDR design, we not only suppress the self-interference and other noises, but also *double* approximately the received signal strength. This significantly improves SNR of the retroreflecting link. Our prototype shows that it achieves an average of 5.3 dB SNR gain at different distances compared with the status-quo [9].

4.3 Receiver Design

In addition to polarization-based differential reception, our system adopts the on/off excitatory carrier, trend-based modulation and a miller codec design from [9], but with the following modifications.

The excitatory carrier at (high) frequency f_u enables RetroI2V to filter out the low-frequency component such as ambient light noise. The carrier waveform originated from Reader can be expressed as:

$$I_{tx} = I_0 S(f_u t)$$

where $S(t) = 1/2 + (1/\pi)\sum_{i=0}^{\infty} \sin(2\pi(2i+1)t)/(2i+1)$ is the unit digital square wave function (Fig. 3 ❶). Suppose the signal is retroreflected by a RetroSign at distance d with path loss $A(d)$, after the round-trip transmission, the received waveform at Reader becomes

$$I_{rx} = I_0 A(d)^2 S\left(f_u\left(t - \frac{2d}{c}\right)\right) I\left(t - \frac{d}{c}\right)$$

where $I(t)$ denotes the LC-modulated (retroreflection) waveform at time t, and c is the speed of light. However, the demodulator that unloads signal from the carrier now should be carefully chosen: rectifier or envelope detector is incompatible with PDR because the subtracted signal (❷ ❸) after discarding the DC and harmonics (❹) is no longer amplitude-modulated but phase-modulated (BPSK). Note that the carrier of reflected signal after bandpass filter has two features: 1) only the fundamental frequency, *i.e.,* $(1/\pi)\sin(2\pi t)$, of the carrier remains; 2) it is actually originated from the Reader itself, so there would be only a phase shift to the original carrier due to propagation delay. Therefore, we reuse the locally generated carrier and adopt a co-carrier homodyne (I/Q) demodulator design from popular COTS RFID systems [27] with circuitry customization to mix two orthogonal carriers, *i.e.,* multiplying I_{rx} by $\cos(2\pi f_u t) - j\sin(2\pi f_u t) = e^{-2\pi j f_u t}$:

$$\begin{aligned} I_{rx\text{-}mixed} &= I_0 A(d)^2 I\left(t - \frac{d}{c}\right)\frac{1}{\pi}\sin\left(2\pi f_u\left(t - \frac{2d}{c}\right)\right)e^{-2\pi j f_u t} \\ &= \frac{1}{2\pi j} I_0 A(d)^2 I\left(t - \frac{d}{c}\right)\left(e^{-2\pi j f_u\left(\frac{2d}{c}\right)} - e^{-2\pi j f_u\left(2t - \frac{2d}{c}\right)}\right) \end{aligned}$$

The mixed signal comes out to be a superimposition of a high-frequency component and a baseband signal. We define the baseband signal as the complex signal (❺) for further demodulation:

$$I_{rx\text{-}b} = \frac{1}{2\pi j} I_0 A(d)^2 I\left(t - \frac{d}{c}\right)e^{-2\pi j f_u\left(\frac{2d}{c}\right)}$$

In addition, the adopted modulation and coding schemes together overclock the LC modulator, and the resulting distorted waveform is handled by a soft-input maximum likelihood decoder for information bits recovery – the soft-input (*i.e.,* normalized waveform) was profiled through explicit channel estimation of propagation loss and DC bias. For our system, we extend the linear regression formulation used in [9] to work with complex number for channel estimation:

$$\{\hat{a}, \hat{b}, \hat{t}\} = \underset{a,b\in\mathbb{C},t>0}{\operatorname{argmin}} \int_0^{T_p} |I_{ref}(\tau) - (aI_{rx\text{-}b}(\tau + t) + b)|^2 \mathrm{d}\tau$$

where $I_{ref}(\tau)$ denotes the real-valued reference signal waveform of the symbol of length T_p, a and b indicate the complex attenuation (from phase shift and path loss) and offset (resulting from PDR residual due to carrier leakage and/or imperfect photodiode placement realizing PDR) between $I_{rx\text{-}b}$ and I_{ref} respectively. The final optimum residual indicates the noise level.

Finally, note that the resulting baseband signal $I_{rx\text{-}b}$ is essentially an attenuated and (phase) delayed version of I_{tx} – this delay, or argument of estimated complex attenuation, or rotation in the complex plane of $\varphi = 4\pi f_u d/c$ (❺), is proportional to the distance d between two ends[3]. This byproduct experimentally achieves sub-meter level ranging accuracy and facilitates our real world mobile experimental evaluation (Fig. 10g).

[3]The 455 kHz on/off carrier corresponds to a wavelength larger than 600 m, so the phase does not wrap within the working range.

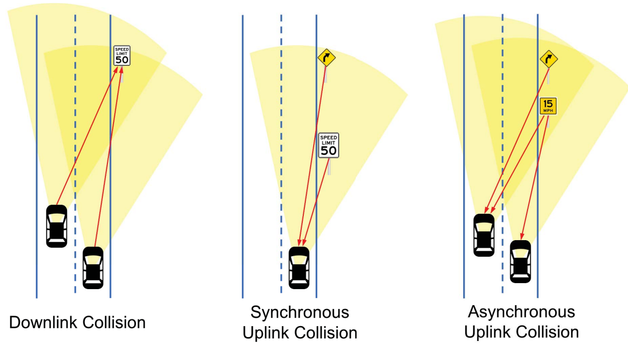


Figure 4: Illustration of different collision scenarios.

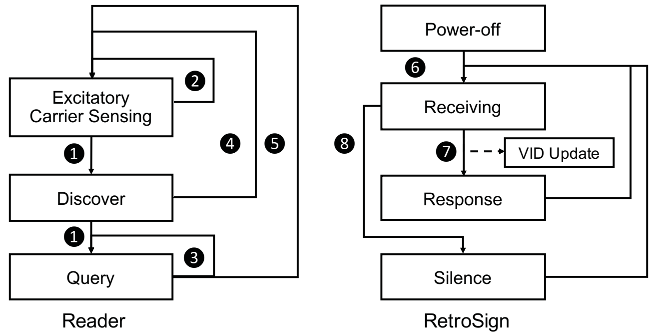


Figure 5: States and transitions in RetroI2V end devices: ❶ One-to-one communication, the normal communication case. ❷ Overhear other ongoing session. ❸ Loop over multiple RetroSigns. ❹ Downlink collision or no RetroSign in view. ❺ Communication ended or aborted. ❻ Powered on (by incoming light). ❼ On-target communication. ❽ Downlink collision or off-target suppression.

5 RETROI2V MAC LAYER

This section presents our decentralized multiple access MAC protocol design, its basic operation flow, optimizations to improve the efficiency and discussion on practical real world usage.

5.1 Design Considerations

Periodic Broadcasting vs. Query and Response. Road signs are of local broadcasting nature. They are designed to convey location-specific information to all oncoming vehicles. The retroreflection-based LC modulation design of RetroSign also conforms to the local broadcasting nature of road signs. Indeed, the toggling of liquid crystal states will affect *all* incident lights, regardless of their sources and carrier frequencies. Realizing this, one tends to think of a periodic broadcast beaconing mechanism for I2V message delivery for its simplicity. Unfortunately, this is not the case in practice: when there are multiple RetroSigns in the view of a Reader, their responses will doom to collide. That is, all RetroSigns in proximity are potential colliders. Yet, it is almost impossible to statically coordinate them for a couple of reasons. Firstly, for sake of low-power requirement, RetroSigns are designed to be reactive. They cannot sense the existence of other RetroSigns in proximity. Secondly, the *de facto* proximity is highly dynamic due to the mobility of Readers (*i.e.,* different positions) and the diversity of headlight power (*i.e.,* different viewing scopes). Thirdly, to save energy, a RetroSign may sleep from time to time and may become activated at different time. It is difficult to keep a global clock and ensure clock synchronization among nearby RetroSigns. These reasons necessitates the design of a query and response MAC model.

Collision Case Analysis. There are three kinds of collisions under different situations, as illustrated in Fig. 4.

• *Downlink Collision:* This happens when a RetroSign is in common view of multiple Readers and when more than one Readers attempt to talk to the same RetroSign at the same time. This is the *many-to-one* communication situation.

• *Uplink Collision:* When multiple RetroSigns are in the view of a Reader and are interrogated at the same time, they may respond simultaneously and lead to a *synchronous uplink collision*. This corresponds to the *one-to-many* communication situation. In *many-to-many* communication situation, when a first RetroSign is responding to a first Reader and a second Reader nearby attempts to interrogate a second RetroSign that happens to be within the view of the first Reader, the uplink response of the second RetroSign (to the second Reader) will be overheard by the first Reader and thus corrupts the first RetroSign's ongoing response. This will result in *asynchronous uplink collision*. Notice a special case of uplink collision – *capture effect*, where the response from an intended RetroSign is overwhelmed by response(s) from another unintended RetroSigns that may have much (*e.g.,* an order of magnitude) larger reflective surface or shorter distance to the Reader, or their combination. Captured RetroSigns can be rescued later as the capturing situation gets changed due to the mobility of Readers.

5.2 States and Transitions

For a Reader, there are three basic states, namely *excitatory carrier sensing* (ECS), *Discover* and *Query*. In the ECS state, it keeps emitting a carrier at one frequency f_u to probe any ongoing communication sessions. When encountering new RetroSigns, it will try to query all of them, one by one excluding those already heard. When in *Discover* and *Query* states, it performs active downlink transmission at another carrier frequency f_d. For the rest of time, it resides in the ECS state. For a RetroSign, it has three states, namely *Receiving*, *Response* and *Silence*. It normally resides in a power-off state and becomes active when interrogated by incoming light carrier(s).

Fig. 5 shows the basic states, their transitions and triggering conditions of a Reader and a RetroSign in RetroI2V. From the figure, we see that, normally, Reader's states will change sequentially. When there are collisions, as will be analyzed below, Reader actions (Discover or Query) will fail and will be retried after certain backoff. Different collisions lead to different state transitions. For a RetroSign, upon activation by incoming carrier(s), it enters the Receiving state. After receiving downlink message, it may respond immediately if it is an intended communication target, or it remains silent until it is queried.

5.3 Message Type and Format

To facilitate MAC protocol operations, we designed five messages, namely Discovery Request (DReq), Query Request (QReq), Query ACK (QAck), Discovery ACK (DAck), and Query Response (QResp). The former three are downlink messages and the latter two are uplink messages. In particular, DAck is a very short waveform with special pattern for presence detection, and QAck is piggybacked

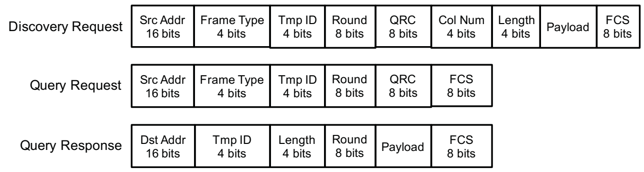


Figure 6: Message frame format.

in DReq or QReq message to reduce downlink traffic, as will be elaborated later in this section. Fig. 6 depicts the frame format of the rest three major MAC messages.

Among all the fields in a MAC message, the `Round` field indicates the ordinal index of current discovery round. The `Tmp ID` field is a random number used to resolve uplink collisions. It serves as a temporary ID for the RetroSign and is specific to the Reader. The `QRC` field is the CRC value computed from the payload in a previous QResp the Reader received. This field is for the RetroSign to verify if its QResp is successfully delivered, by comparing QRC value against its local CRC of payload. The `FCS` field is the CRC for the current frame.

As the knowledge about the presences and IDs of RetroSigns cannot be known a priori to a host vehicle, it has to be be discovered first. It is infeasible to pre-assign a fixed GUID to each RetroSign because it would require national-wide or industry-wide agreement on address assignment and a very large address space have to be used which would imply an unaffordable long discovery process. Note however, given our distributed MAC, we need to discover and discriminate *only those RetroSigns appearing in the view of the same Reader*. It does not matter if the ID of a RetroSign is consistent or not in views of different Readers. Realizing this fact, we design a *Virtual ID* (VID) scheme in which a temporary, Reader-specific ID is generated on the fly, under the guidance of the Reader. Concretely, A RetroSign constructs its VID by concatenating Reader address (`Src Addr`), current discovery round index (`Round`), and a temporary ID (`Tmp ID`). The former two are directly sent by the Reader in the DReq message. `Tmp ID` is locally generated at RetroSign. It follows $unif\{0, 2N_c\}$ with N_c being the number of uplink collisions in last discovery round which is also carried in the DReq message. Note that all the possible values of `Tmp ID` constitute the *VID candidate list* maintained at the Reader. The Reader will increment N_c, and expands its VID candidate list accordingly, if an uplink collision happens or reset to 0 after a success discovery. As a remark, this (short) 5-byte header is our best effort design that takes into consideration the limited uplink rate, number of in-view RetroSigns on the road in most real world cases, and all the necessary protocol meta information.

5.4 MAC Operations

Fig. 7 shows the workflow of Reader's discovery and query processes and also highlights where different collisions may happen and how they are handled.

5.4.1 Excitatory Carrier Sensing

As aforementioned, in the ECS state, a Reader keeps emitting a carrier (at frequency f_u, different from that f_d used in active communication sessions) to probe ongoing communications. This carrier will excite a RetroSign if it is not active yet. This is an exploitation of the sharp directionality of the retroreflective light path and

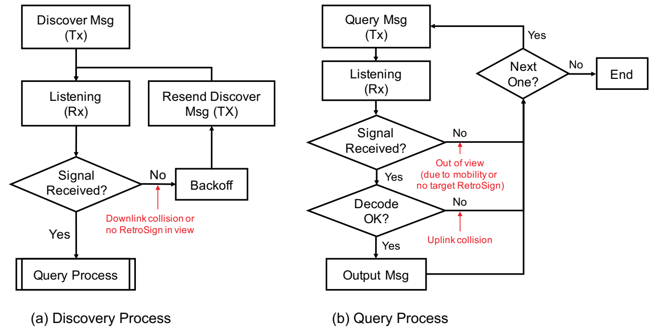


Figure 7: Workflow of discovery and query processes.

the frequency-agnostic feature of LC modulation. Thus, when a RetroSign is responding to another Reader's discovery or query through LC modulation, the retroreflected light from any Reader in ECS state will also get modulated simultaneously. This allows the Reader to sense any ongoing communication session, and even to overhear the message, and to ensure the channel is idle before attempting its own discovery or query.

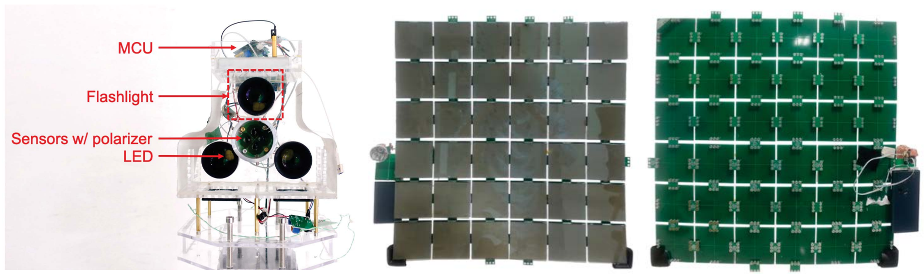
5.4.2 Discovery and Query Processes

Discovery Process. When ECS concludes the channel is idle, the Reader enters Discovery state. It broadcasts a DReq message and then listens to the channel. If energy is detected within the timeout period (*e.g.,* 30 ms), the Reader is receiving DAck as any RetroSign in reach would respond with a DAck. It enters Query state afterwards. If no signal is detected via energy detection till timeout, it concludes there is either no RetroSign in view or *downlink collision* might have happened as a RetroSign will remain silent for the same timeout when it receives multiple concurrent discovery messages. In this case, the Reader performs a random backoff. When backing off, it enters ECS. If not overhearing anything, it will try again when backoff timer fires. During the process, the Reader also forms a VID candidate list covering the address space of all the RetroSigns it will query then.

Query Process. The Reader then enumerates the VID candidate list and query each candidate via a unicast QReq message. By default, a RetroSign will respond with a QResp message if its VID matches that in the QReq. Similar to the Discovery process, it performs energy detection to conclude if there is a response from the RetroSign or not. If not, it means the RetroSign is out of view and it will proceed to the next RetroSign on the list. If there is signal detected, it will try to decode the message. If successful, it outputs the message, removes the RetroSign from the VID candidate list, and moves on to the next VID. Otherwise, it concludes an *uplink collision* has happened in receiving the uplink message and will retry the failed RetroSign in the next query round.

5.4.3 Collision Handling and Optimizations

Collision Detection and Resolution. All collisions are detected from the fact that received signal cannot be correctly decoded, either at the Reader side for downlink collision or at the RetroSign side for both synchronous and asynchronous uplink collision. Downlink collisions are handled with random backoff and retrial. As downlink is typically much faster than uplink, the backoff time is not considered as a large overhead in the session. Uplink collisions are handled via on-the-fly expansion of VID candidate list.



(a) Reader

(b) RetroSign (front and back)

Figure 8: RetroI2V prototype.

Figure 9: Experimental setup.

Optimizations. In practice, uplink is more than an order slower than downlink due to the limitation of the COTS LCD's response time. To counteract this and boost MAC efficiency, we have applied several optimizations.

• *Overhear-before-talking:* When ECS senses channel busy, the Reader will suppress its discovery or query. Instead, it tries to overhear first at the excitatory carrier frequency. So if timing is good, it may overhear the whole message and suppress its own query. This will not only greatly mitigate asynchronous uplink collision due to query suppression, but also be helpful in resolving downlink collisions, as the further backed-off Reader will have a good chance to overhear the winning Reader's query. Evidently, this attributes to the design choice of using a different carrier frequency for ECS and the fact the RetroSign is agnostic to incident carrier frequencies. Note that the Reader no longer needs to generate VID for the RetroSign it overhears, but will do so for the rest.

• *Aggregating and Piggybacking:* These are to reduce rounds of communications. First of all, we have aggregated the first discovery message and a normal query. That is, a first DReq message from a Reader also serves as a QReq. This is to improve the efficiency for the most common one-to-one communication situation. A Reader will piggyback QAcks (with VID) to all the RetroSigns it has received, including those overheard during previous backoff period, in the payload field of its next message, either DReq or QReq. RetroSigns received the message will compare its VID and that carried in the QAck. It will suppress its response if the VIDs match, hence reduces contention for uplinks.

5.4.4 Practical Operation with Headlight

As an implicit assumption, RetroI2V's operation requires an "always-on" headlight, which might seem to be impractical at first glance – lights are typically turned off to avoid dazzling cars and humans from opposite directions. We would like to point that this concern can be readily addressed with advances in recent headlight innovation. For instance, Matrix Multibeam system technology (*e.g.,* Audi, BMW and Mercedes) will automatically deactivate corresponding individual LED units when cars or people from opposite direction are detected (via a front camera) in the light field of headlights, and reactivate those LED units when cars/people have moved away from their corresponding light field [28]. Given RetroI2V is a visible light networking technology, it can be naturally integrated with such anti-dazzling technologies for headlight intelligence enhancement. Note that the dazzling avoidance operation potentially leads to temporary link failure, turning into either downlink or uplink collisions, which will be detected and handled by the MAC protocol.

6 IMPLEMENTATION

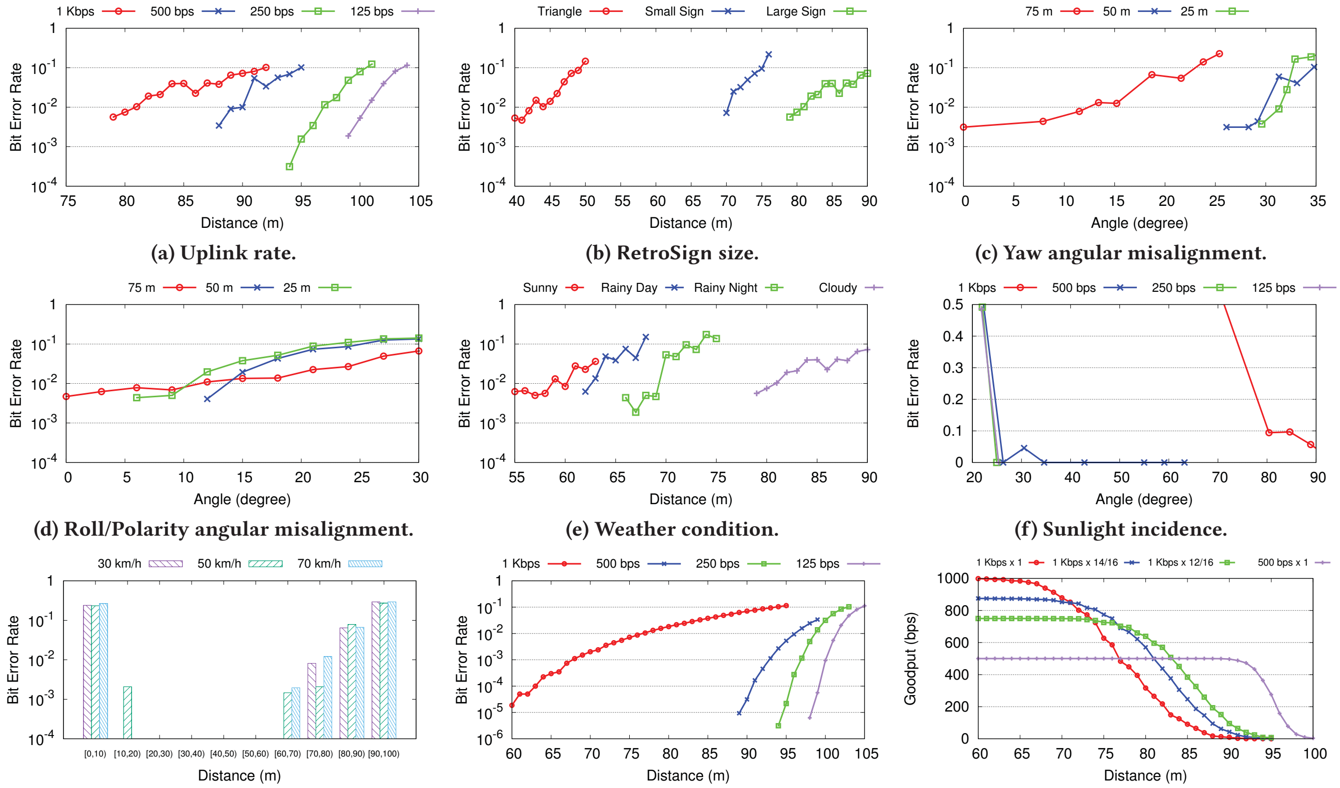
Our prototyping efforts span the design and implementation of hardware and software for both Reader and RetroSign. The software implements the transmission logic and MAC protocol. Here, we elaborate the hardware implementation.

Reader. Our Reader prototype (Fig. 8a) is composed of LED light sources, a customized optical frontend, and a control circuitry with Cortex-M7 MCU. As COTS headlights are difficult to instrument light sensors which need to be co-located with LED bulbs, we have adopted a bundle of three flashlights to emulate a real headlight. We fix the total transmission power as 30 W to meet the power regulation requirement, and adjust its FoV (via the customized optical frontend) to ensure the measured light intensity equals to that of a COTS headlight. The receiving data path follows a regular RFID reader design, and is built with discrete circuitry parts to work with our customized low frequency carrier[4]. Specifically, we choose f_u = 455 KHz and f_d = 1.8 MHz as the uplink and downlink carrier frequency due to standard filter/LC tank availability. The frontend consists of paired photodiodes that are covered with a pair of polarizers with perpendicular directions, and they parallel oppositely to differentiate their photocurrent for PDR and hence suppressing self-interference. Lenses are added in front of photodiodes to concentrate the view of photodiodes to match the lighting field of LED lights and boost signal strength meanwhile.

RetroSign. It consists of a control circuit board with an MSP430G2403 low-power MCU and a large retro-reflection surface which is formed by wiring together an array of small retro-reflective tiles. Each tile is made of a retroreflective fabric and an LCD with front polarizer being peeled off (*i.e.,* moved to the frontend of a Reader). In our implementation, the RetroSign measures 0.3 m^2 and consists of 36 small tiles, see Fig. 8b. To emulate traffic signs with various sizes and shapes, we may selectively disable a subset of these tiles.

Cost Analysis. The cost of RetroI2V is more than 10 times less than that of the DSRC solution, for both OBU on host vehicles or RSU on road side. The BOM cost of our prototype is $70 for the Reader and $38 for the RetroSign. Note that 90% of the RetroSign cost is spent on LCDs, which would surely be significantly reduced at mass production – its low cost is the key to facilitate massive deployment in the wild.

[4]Note that phosphor LEDs have a maximum bandwidth of several MHz.



(a) Uplink rate. **(b) RetroSign size.** **(c) Yaw angular misalignment.**

(d) Roll/Polarity angular misalignment. **(e) Weather condition.** **(f) Sunlight incidence.**

(g) Mobility. **(h) Emulation.** **(i) Error correction coding gain.**

Figure 10: PHY experimental results.

7 EVALUATION

7.1 PHY Performance

7.1.1 Experimental Setup

We have evaluated RetroI2V in different environments and different weather and lighting conditions, as shown in Fig. 9. As the uplink rate (1 Kbps), bit error rate, RetroSign size (large, 0.3 m^2), communication distance, relative angular separation between the Reader and the RetroSign (perpendicular), and experiment environment (clear night) are all interrelated, in the results below, unless explicitly experimented with, all the factors are set to their default values, *i.e.,* those in parentheses. We use bit error rate (BER) as our primary PHY performance metric. We judge a communication range to be reliable only when its BER is lower than 1%. For each data point, we send 25 packets, and each packet is of 16 bytes.

7.1.2 Results

Uplink Rate. From Fig. 10a, we can make several observations. First, long communication range is achievable. Even with 1 Kbps uplink rate, a Reader can talk to a RetroSign from 80 m away and meet the long range requirement (§3.1). Secondly, the uplink rate inversely affects the range. This is because a lower rate implies longer symbol time, which allows deeper liquid crystal state changes, hence larger disparity between retrieved signals at the Reader. Thirdly, for the same uplink rate, the BER drops quickly when the communication range gets shorter. Finally, for distances reachable by multiple uplink rates, the resulting BERs differ. This suggests a space for optimal rate selection.

RetroSign Size. We experimented with a large RetroSign (sized 0.3 m^2), a small one (0.15 m^2) and a warning triangle sized (0.025 m^2) RetroSign. The results are shown in Fig. 10b. As expected, larger RetroSign size leads to longer communication range. Interestingly, the relation seems highly non-linear, *i.e.,* halving the size does not lead to half communication distance. Even for the smallest warning triangle, a Reader can communicate with it from 45 m away.

Yaw Angular Misalignment. A RetroSign is normally deployed alongside or atop a road, upright and perpendicular to the road direction. As the road is not always straight and a vehicle may change lanes, it is possible that a Reader does not (always) face a RetroSign squarely (*i.e.,* the center line of Reader's FoV is not parallel to the normal of RetroSign). We measured how RetroI2V tolerates such misalignment. The results are shown in Fig. 10c. We see that the yaw angular tolerance is about $\pm 12^\circ$ at 75 m, and increases to almost $\pm 30^\circ$ when the distance is reduced to 50 m. The general trend holds: when a Reader gets closer to a RetroSign, the yaw angular tolerance increases.

Roll/Polarity Angular Misalignment. Our PDR scheme works best when the two polarizers on a Reader are either aligned or orthogonal to that on the RetroSign. However, a roll of a Reader (*e.g.,* on a curved slope) will cause polarity misalignment with a normal RetroSign. From Fig. 10d, we observe that RetroI2V can tolerate misalignment in roll angle as high as $\pm 18^\circ$. This, however, is less affected by the communication distance, as compared with previous yaw angular tolerance experiments.

Weather Condition and Ambient Light. We have conducted experiments under different weather conditions[5]. The results are presented in Fig. 10e. We may intuitively conclude that RetroI2V works better under cloudy weather and at night. Rain attenuates light signal, while sunshine may increase quiescent current of photodiodes and hence the noise floor. Nonetheless, our experimental results show that RetroI2V can still achieve communication distances of 60 m, 62 m and 69 m in sunny days, rainy days and rainy nights (with raindrops on top of the photodiode on Reader and RetroSign surface), respectively. Finally, note that ambient (polarized) light reflection from on-road sources such as ground, vehicles, and their paintings and windows are essentially DC or low-frequency signals. We experimentally verified that they can be easily eliminated by our bandpass filter and cause no interference to Readers.

Sunlight Incidence. As sunshine will elevate the noise floor and increase BER, we further study the impact of its incident angle. In the experiments, the Reader-RetroSign distance is fixed to 20 m. From Fig. 10f, we can see that: 1) small incident angle (*i.e.,* the sun appears near the center of a Reader's FoV) will fail a Reader; and 2) higher uplink rate is more affected by direct incident sunlight. In particular, for uplink rate lower than 500 bps, a Reader will work normally when the incident angle is over 24 °. However, for 1 Kbps uplink rate, the Reader can work only when the incident angle is over 80 °. This is because the demodulation threshold (*i.e.,* SNR requirement) for 1 Kbps mode is too high in our prototype implementation. A sun shield will also help.

Mobility. We have carried out mobility experiments at three velocities, *i.e.,* 30, 50 and 70 km/h with the RetroSign operating at 1 Kbps. For each velocity, RetroI2V transmits at least 1280 bits (*i.e.,* 10 packets) in total for each 10-meter distance interval, over which we calculate the average BER. As shown in Fig. 10g, RetroI2V is able to keep BER below 1% for the range between 10 m and 80 m, and even achieve 0 BER in the range of 20 m to 60 m. BER exceeds 10% at the distances less than 10 m. This results from approaching the boundary of FoV of the Reader and also a large incident angle θ to the RetroSign, which causes a significant reduction in effective reflection area (*i.e.,* by $\cos\theta$). Overall, our evaluation results suggest that RetroI2V can achieve reliable communication over a long range even at high mobility of 70 km/h or even higher.

Emulation. We further carried out a set of emulation-based experiments to better understand RetroI2V's performance in different channel condition, *i.e.,* BER under different SNR respect to distance. We collected the reference waveform of symbols at different rates, signal-distance profile and noise pattern from real experiments, and then generated the emulated waveform by superimposing the noise upon the signal corresponding to the strengths of different distances. For evaluation, the BER result for each data point is based on 2500 emulated packets (*i.e.,* 320000 bits). As shown in Fig. 10h, our emulation results not only show high consistency with real-world experiments, but also report the much lower BER results under shorter distance.

[5]We did not encounter foggy weather during the experimental evaluation period. A recent study [29] reported that heavy foggy weather (with visibility of 50 m) may lead to 27% reduction in VLC range as compared to clear weather. We believe RetroI2V would perform reasonably well in ordinary foggy weather.

Error Correction Coding Gain. To further study the end-to-end link performance, we applied Reed-Solomon Code [30] to our emulation-based experiment and compute goodput based on the simple stop-and-wait retransmission mechanism with different k, where $k/16$ is the coding rate for each 16-byte (codeword) packet. Note that error correction code naturally yields a trade-off between packet loss rate and data rate – a smaller k enables a stronger error correction ability while decreasing the goodput. As shown in Fig. 10i, we observe that error correction code of lower coding rate keeps benefiting goodput when SNR approaches the demodulation threshold from a greater distance.

Link Budget Analysis. In practice, road signs can be much larger than our prototype, or they can be built with larger size for longer range. Based on the link budget model [9], we can estimate that our Reader can talk to a highway guide signs of 2.8 m^2 from 244 m away at 1 Kbps, and discover a RetroSign warning triangle from 116 m away if narrowing down its FoV from 30 ° to 4 ° based on beam steering [31].

RetroSign Type	Size	Backscatter
Large Traffic Sign	0.3 m^2	19.19 µJ/bit
Small Traffic Sign	0.15 m^2	10.18 µJ/bit
Warning Triangle	0.025 m^2	2.69 µJ/bit

Table 1: RetroSign's energy consumption at 1 Kbps.

RetroSign Power Consumption. Tab. 1 shows the energy profiling results for RetroSigns with various sizes using Monsoon [32] when the uplink operates at 1 Kbps. The results indicate that a RetroSign consumes two or three order of lower power than active VLC/RF-based technology. Evidently, this helps to significantly extends the battery life and lower the bar of long-term deployment.

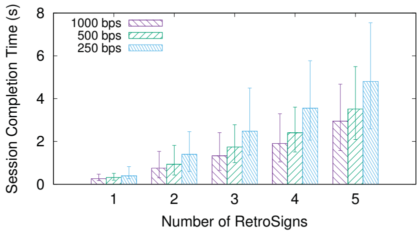
7.2 MAC Performance

7.2.1 Lab Experimental Results

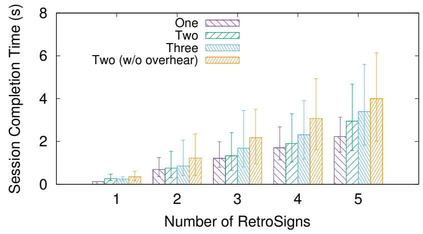
We first conducted small-scale experiments to prove the effectiveness of RetroI2V's MAC protocol. We set up 3 Readers and 5 RetroSigns, with Readers facing RetroSigns squarely. We ran 100 experiments for each test. In each test, all Readers need to retrieve content from all RetroSigns. All Readers are started simultaneously. We use average *session completion time* as the performance metric. In default settings, we used 2 Readers, 5 Kbps downlink rate, 1 Kbps uplink rate and 1-byte payload. Note that co-located RetroSigns and simultaneous starting represent the most challenging situation.

Uplink Rate. The network latency can immediately benefit from a faster uplink. As shown in Fig. 12a, with our MAC protocol, the session completion time decreases 28.14% and further 14.08% when the uplink rate increases from 250 to 500 and 1000 *bps* respectively.

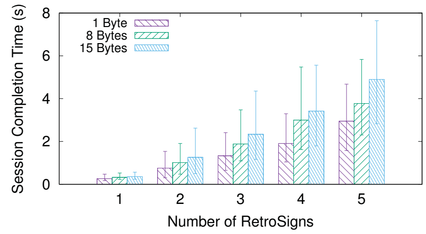
Number of Reader. More Readers will certainly invite more downlink collisions and introduce longer delay in discovering all RetroSigns. As shown in Fig. 11b, the session completion time increases by 34.71% and 49.64% with one and two additional Readers, respectively. The results also confirm the effectiveness of the *overhear* mechanism in our MAC design. Specifically, the session completion time for two Readers without overhear mechanism is even longer than that of three Readers with overhearing.



(a) Uplink rate (two Readers).

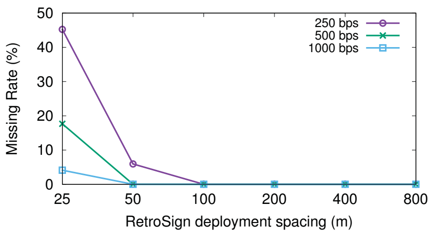


(b) Number of Reader.

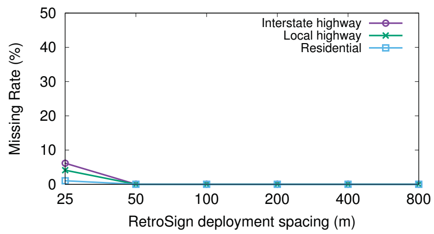


(c) Payload length.

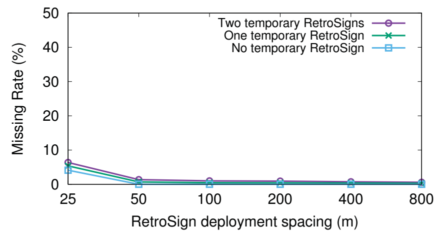
Figure 11: MAC experimental results.



(a) Uplink rate.



(b) Road traffic.



(c) RetroSign density.

Figure 12: MAC large-scale simulation results.

Payload Length. From Fig. 11c, we see that the session completion time increases gently with longer payload. Compared to the case of 1-byte payload, the delivery time increases by (only) 37.04% and 64.94% for 8x and 15x payloads respectively, which suggests longer payload is preferable given the PHY and MAC overhead.

7.2.2 Large-scale Simulation Results

We further complemented our experimental evaluation with extensive simulation to study RetroI2V's performance in practical I2V scenarios. We use *Missing Rate*, a common performance metric for RFID systems, as the metric. It measures mean percentage of the RetroSigns failed to deliver content to an interrogating Reader during their encountering period. We ran 100 times for each setting and report the average results. The code is released in [33].

Parameters Description. We consider three key parameters:

• *Uplink Rate.* It affects not only the session completion time (hence the potential collisions due to Reader mobility), but also the effective communication range. We leverage the PHY experiment results and obtain maximum communication ranges (*i.e.,* those at 1% BER) for different uplink rates, and further apply the Lambertian model [34] to determine the lighting scope of a headlight.

• *Road Traffic.* We consider three cases: a residential area road of 1 lane, a local highway of 2 lanes and an interstate highway of 3 lanes with 30, 50 and 70 mph speed limit, respectively. Road surface is full of vehicles while keeping 2-second safe trailing distance, *i.e.,* the average number of host vehicles is 4.34, 3.77, 2.88 per 100 m with residential area road, local highway, interstate highway respectively. Vehicles on different lanes have random initial location. We use 3.5 m and 2.5×4.5 m as lane width and vehicle's dimension. RetroSigns are deployed 1 m off the roadside.

• *RetroSign Density.* In the real world, traffic signs are usually deployed sparsely. In general, the higher speed limit, the sparser traffic signs. We keep the RetroSign deployment spacing as a common parameter to evaluate. We also invite extra RetroSigns deployment between the two regular RetroSign to simulate the temporary warning triangle scenario.

In the default setting, host vehicles are traveling in the local highway with 2 lanes at 50 mph and communicating with large RetroSigns operating at 1 Kbps.

Uplink Rate. Fig. 12a shows that when RetroSigns are densely deployed, *e.g.,* every 25 m or 50 m, the uplink rate plays an important role in reducing the missing rate – it drops from 45.23% to 17.66% and 4.11% when the rate is doubled from 250 bps to 500 bps to 1000 bps for every 25 m RetroSign spacing. A faster uplink has two favorable implications: 1) shorter uplink latency leads to increased network capacity, and 2) the shorter communication range reduces potential uplink collisions. Specifically, when RetroSigns are deployed every more than 100 m, the missing rate drops to 0 because there is almost no uplink collision.

Road Traffic. As shown in Fig. 12b, we observe RetroSign miss for all the three cases when RetroSigns are deployed every 25 m. Interestingly, the interstate highway scenario has the fewest Readers, but yields highest missing rate, *i.e.,* 6.16% in comparison to 4.11% and 1.02% for the other two scenarios. This is because the Reader on left lanes has shorter encounter time for each RetroSign, leading to less time seeing multiple RetroSigns and consequently less uplink collision and miss – the missing rates are 2.05%, 5.56% and 10.87% from left to right lanes. As an extreme case study for futuristic driverless car fleet scenario in which cars will not only move very fast but also keep short following distance, RetroI2V can support up to 15.9, 21.7 and 26.4 Readers every 100 m of road segment by keeping the missing rate under 1% when RetroSigns are deployed every 50, 100 and 200 m respectively in the (3-lane) interstate highway scenario. Moreover, when downlink rate is boosted from 5 Kbps to 10 Kbps, we can fully support the most extreme fleet case, *i.e.,* 44.4 Readers tightly following each other when RetroSigns are deployed every 50 m or longer distance. We note that in our study we did not consider the potential inter-vehicle blockage or non-line of sight problem. This is because traffic signs are typically deployed (or to be retrofitted) in a position high enough to be visible for human eyes through retroreflection, and hence retroreflective communication.

RetroSign Density. In this set of simulations, we consider the irregularity of traffic sign deployment in the real world. Fig. 12c shows that higher density of RetroSigns always yields higher missing rate. For instance, when RetroSigns are deployed every 25 m, one and two extra RetroSigns randomly deployed in between will lead to increases in the missing rate, from 4.11% to 5.38% and 6.36% respectively. When the inter-RetroSign spacing increases to 800 m, uplink collision can still happen with a low possibility from the temporary RetroSign deployment – the missing rate for one and two is 0.28% and 0.58% with 5.38% and 8.76% uplink collision rate.

7.3 Summary of Key Results

Our evaluation demonstrates it is *feasible* to renovate traffic signs under tens of dollars budget, establish a *reliable* retro-communication link up to 101 m and robust to ambient lighting condition, mobility level, *etc*., and achieve *scalable* decentralized multiple access in practical I2V networking scenarios. As a remark, we have used a 0.3 m^2 RetroSign in our experiments. Practical traffic signs are of much larger area. We expect even longer communication range and better system performances in real deployment.

8 DISCUSSION

Prioritize RoadSigns. Road signs (including portable Warning Triangle) may be regulative or informative, emergent or less important. It is a desire to support prioritization in the I2V communications. It is possible by modifying the MAC protocol and make the high priority RetroSigns to reply first and less prior RetroSigns delay their response after the fixed duration of a Discovery ACK packet.

Uplink Rate. As other VLBC schemes do, RetroI2V's uplink also suffers from low data rate which is constrained by the low toggle rate (*e.g.,* 100 – 240 Hz) of the COTS LCD. Much faster switching liquid crystal (*e.g.,* CCN-47 with 30 ns restoration time [35]) has become technically viable. The potential wide application of RetroI2V, together with other VLBC scenarios, might be a driving force towards earlier mass production of faster LCDs.

Security and Reliability. Current RetroI2V does not offer any security property. We assume RetroSigns' information is public in nature. While our MAC protocol allows retransmission, it is more intended to mostly work in a best-effort way. This is partially due to the highly transient networking in I2V. Nonetheless, slower speed offers more time for retrials.

9 RELATED WORK

Vehicular Visible Light Communication. Other than DSRC [36–38], visible light is also recognized as a compelling solution for vehicular networking [39, 40]. The concept of visual MIMO [41] was proposed to use LED and photodiode arrays such as taillight and front camera to form visible light MIMO communication links and deliver safety information. In [42], the authors experimentally demonstrated V^2LC network links using LED and photodiodes in the context of V2V are resilient against visible light noise and interference under working conditions. The focus of our work is I2V and thus is complementary to these existing approaches.

Passive Visible Light Communication. In contrast to traditional active VLC [41, 43–56], the idea of passive VLC, *i.e.,* piggyback information through light reflection, has been recently exercised. By employing LCD(s) as an optical modulator, the series of work realized a retroreflecting link over the incoming light (carrier) from existing indoor lighting infrastructure using OOK [9, 20] and PAM [23]. The work [57, 58] embeds barcodes onto the surface of mobile objects and realizes passive communication by reading the optical pulse reflection from ambient light. The noise suppression design in RetroI2V can extend range in all the aforementioned work.

Polarized Light Communication. PIXEL [21] leveraged dispersor to translate (relative) polarization direction into color and devise Binary Color Shift Keying modulation with fine dispersion tuning to maximize the intensity difference of the two states in all receiving orientations. POLI [53] combines three light sources of different polarization directions with a dispersor and map their transmitting intensity to the received RGB values to realize polarization intensity modulation. The work [22] presents a light polarization pattern realized by a polarizer and birefringent film for grid-level positioning and a dual-sensor design that examines the differential color values of two collocated color sensors to remove ambient light noise. Our design shares the same philosophy of using polarization(-based modulation), but achieves self-interference suppression in retroreflective communication.

MAC Protocol for Backscatter Networks. Most existing works are focused on radio backscatter networks. To our best knowledge, they either only support one-to-many communications like RFID [59], or need a centralized controller for coordinating multiple readers [60–62]. Our design is the first one for visible light backscatter networks. It is fully decentralized, supports many-to-many communications, and works for directional networking environment.

10 CONCLUSION

Retroreflective road signs enable superior visibility at night and have been massively deployed as a cost-effective solution for road safety. Built on the emerging visible light backscattering communication technologies, this paper presents the PHY and MAC design of RetroI2V. The novel design achieves goals of low-power, long-range and reliable networking, easy and gradually deployability, and friendliness to human vision. With the design and extensive evaluation of RetroI2V, we testify the feasibility of empowering retroreflective road signs to disseminate dynamic in-situ information to vehicles while retaining their original function of delivering concise static visual information to human drivers. We believe RetroI2V will play an important role in improving safety and efficiency in future intelligent transportation systems.

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