Optimal Time Partitioning in V2V Integrated Sensing and Communication Systems

Abhilash Gaur*, Ashutosh Balakrishnan*, Seshan Srirangarajan, Swades De, Po-Hsuan Tseng, and Kai-Ten Feng

***Abstract*—Platooning-based vehicle-to-vehicle (V2V) integrated sensing and communication (ISAC) frameworks have emerged as an attractive strategy in recent years. In this work, we present an optimal time partitioning (OTP) framework in V2V ISAC systems. We propose a novel sensing measure for quantifying radar sensing performance as a function of the maximum detectable range and velocity of the radar. With the communication operation following the sensing operation, an OTP problem is formulated and solved as a convex problem, constrained by sensing and communication performance guarantees. Optimal bounds on the time duration for sensing and communication are derived, along with the maximum achievable communication throughput. Furthermore, analytical insights on the inherent trade-offs associated with the design parameters are presented. The simulation results demonstrate that the proposed OTP framework achieves a communication throughput gain of up to 12.6% over the equal time partitioning framework, in addition to meeting the sensing performance requirements.**

***Index Terms*—Integrated sensing and communication (ISAC), vehicle-to-vehicle (V2V) platooning, convex optimization, optimal time partitioning**

I. INTRODUCTION

There has been major recent interest in developing autonomous vehicles, driven by the rapid convergence of artificial intelligence and the next generation communication technologies. Grouping the autonomous vehicles, i.e., platooning, has emerged as a popular driving strategy for road transportation and is envisaged as an important use case in next generation networks [1]. While platooning of vehicles almost always ensures line-of-sight communication between vehicles, it is also very useful in traffic planning and developing vehicle-to-vehicle (V2V) infrastructure. Equipping the platooned vehicles with object sensing and communication hardware is essential for their smooth movement [2].

Integrated sensing and communication (ISAC) has emerged as an attractive strategy to equip platooned vehicles with joint radio sensing and communication hardware, which reduces hardware complexity. Recent studies in [3]–[8] have presented several ISAC frameworks. Object sensing and data communication operations are influenced by multiple design parameters, namely, trasmit power, velocity and range of the object, channel gain, and the time duration allocated for sensing and communication. To the best of our knowledge, there has been no study in the literature that has quantified the optimality of the sensing and communication time durations, and analyzed the influence of sensing and communication design parameters on these time durations. Furthermore, the coupling between the sensing and communication parameters also needs to be studied and quantified in an ISAC system. In this letter, we formulate an optimal time partitioning (OTP) convex problem and report the optimal time durations required for effective sensing and communication in platooned V2V systems.

Next, we motivate and position our work with respect to the recent and related literature. The authors in [3] considered a time division-based ISAC system for a 5G millimeter wave V2V scenario, wherein they presented a queuing model-based frame structure and interference, and delay response analysis. The study in [4] presented a randomized frequency permutation-based approach for an ISAC system to partition the sensing and communication durations, which relied on accurate approximations to the Cramer-Rao bounds on delay and Doppler estimation errors. The authors in [5], [6] considered a time partitioning-based ISAC system. However, it did not address how to determine the optimal sensing and communication durations, and it has been observed to be inefficient in terms of time resource allocation. A design analysis of frequency hopping, frequency modulated continuous wave (FMCW) radar-based ISAC system was presented in [7]. This study is communication-centric and is aimed at maximizing communication throughput while resulting in radar sensing performance degradation. A communication-centric time allocation framework is also presented in [8] for a joint communication and radar detection system based

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on the available data traffic at the transmitter. However, this framework results in poor radar detection performance in the case of high data traffic. Full duplex ISAC strategies, as in [9], are prone to self interference, resulting in reduced system performance. Moreover, such frameworks require additional signal processing to mitigate self-interference, thereby increasing hardware complexity.

The literature discussed above does not consider optimal time partitioning in ISAC frameworks. Intuitively, optimizing the time partitioning in an ISAC system is essential as the time duration affects the sensing and communication performance. Thus, there is a need to study the inherent tradeoffs associated with the sensing and communication design parameters, and obtain optimal closed-form results for the sensing and communication time durations. In addition, the extent of coupling between the sensing accuracy and communication quality of service (QoS) needs to be studied. Following are the key contributions of this work:

- An OTP framework is proposed for the ISAC systems, incorporating and studying the trade-offs among the related sensing and communication design parameters.
- A sensing measure is proposed to model and quantify the radar sensing performance as a function of maximum detectable range and velocity of the target object.
- An OTP problem is formulated, wherein the constraints in terms of the desired sensing and communication performance are incorporated. Optimal bounds on the sensing and communication time duration are derived, providing insights about the coupling between these performance measures.
- Simulation results demonstrate that, in addition to meeting the sensing performance requirement, the proposed OTP framework achieves a communication throughput gain of up to 12.6% over the state-of-the-art approaches.

The rest of this letter is structured as follows. Section II presents the system model. The OTP problem is formulated and solution methodology is described in Section III. This is followed by an extensive discussion of the simulation results in Section IV. Section V concludes this letter.

II. SYSTEM MODEL

An ISAC-based V2V platooning system is considered, wherein a vehicle **A** senses and communicates with another vehicle **B**, at a distance R and moving with velocity V, as illustrated in Fig. 1. The ISAC transceiver system at vehicle **A** comprises of a transmitter (Tx) capable of performing object sensing as well as data communication. Vehicle **A** transmits an FMCW signal to vehicle **B** at the beginning of each time frame. Vehicle **A** senses vehicle **B** through the echo signal captured at the receiver (Rx) of **A**, while data communication occurs at the receiver of vehicle **B**. The sensing and communication operations are carried out in a time division multiplexed manner.

The ISAC system is assumed to have a coherent processing interval (CPI) of duration T, which is partitioned into a sensing duration T_s followed by a communication duration T_c as shown in Fig. 1. The ISAC system operates in a half duplex fashion, such that the communication and sensing operations do not interfere with each other. While the analysis in this work is performed for a single V2V scenario, comprising of two vehicles, the analysis can be generalized to any number of vehicles.

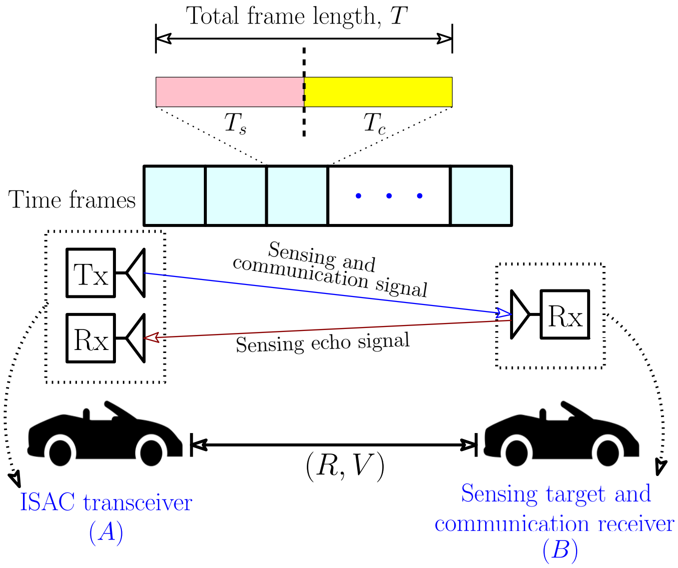


Fig. 1: Illustrating ISAC based V2V system model and timing structure.

A. Sensing Model

In this subsection, we introduce a sensing measure for FMCW radars.

Proposition 1. *We define a sensing measure for an FMCW radar as*

$$C_S = \log_2\left(1 + \frac{8B_sT_sR_mV_m}{c\lambda}\right). \tag{1}$$

Here, B_s denotes the sensing bandwidth, R_m denotes the maximum sensing range, V_m represents the maximum detectable velocity by the radar, T_s denotes the sensing time duration, $\lambda = \frac{c}{f_r}$ represents the wavelength of the radar having center frequency f_r, and c denotes the speed of propagation.

Proof. At the receiver of an FMCW radar, the received signal is de-chirped and sampled with sampling frequency $\hat{f} = \frac{1}{\hat{T}}$ to obtain range-Doppler matrix for parameter estimation. To obtain a sensing measure for radar, each cell in the range-Doppler matrix is assumed to contain a binary value, with 1 representing the presence of target and 0 indicating an unoccupied cell. This assumption together with the Hartley capacity measure [10] allows us to define the maximum capacity of an FMCW radar for one CPI with N chirps as

$$C_S = \log_2(\mathbf{\Gamma}), \tag{2}$$

where, $\mathbf{\Gamma} = MN$ is the total number of independent resolution cells in the range-Doppler matrix, with M being the number of range bins and N the number of velocity bins. The maximum detectable range of an FMCW radar is given as [11], $R_m = \left(cT_s/2B_s\hat{T}\right)$. Substituting $\frac{T_s}{\hat{T}} = M$ in R_m,

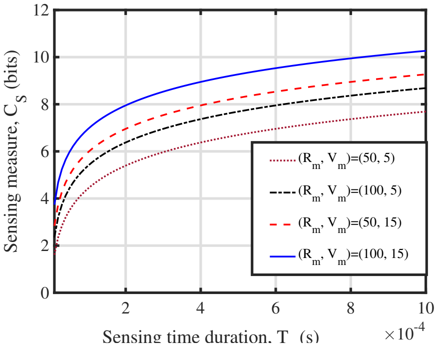


Fig. 2: Proposed sensing measure (C_S) and its concave nature w.r.t. R_m (m) and V_m (m/s).

the number of range bins in the range-Doppler matrix for a given R_m can be obtained as, $M = (2R_mB_s/c)$. Similarly, the maximum detectable velocity V_m by an FMCW radar is given as [11], $V_m = (\lambda/4t_0)$, where t_0 is the chirp duration. Assuming N chirps with chirp duration t_0 are transmitted in one CPI resulting in $T_s = Nt_0$. Substituting $t_0 = \frac{T_s}{N}$ in the expression for V_m, the total number of Doppler bins in the range-Doppler matrix can be obtained as, $N = (4V_mT_s/\lambda)$.

Using M and N, the total number of independent resolution cells in the range-Doppler matrix can be expressed as, $\mathbf{\Gamma} = (8B_sT_sR_mV_m/c\lambda)$. Substituting $\mathbf{\Gamma}$ in (2) yields the capacity expression for an FMCW radar as $C_S = \log_2(8B_sT_sR_mV_m/c\lambda)$. It is noted from this expression that $C_S \to \infty$ as $T_s \to 0$. Thus, the sensing measure is defined as

$$C_S = \log_2\left(1 + \frac{8B_sT_sR_mV_m}{c\lambda}\right). \tag{3}$$

□

We express (3) as $C_S = K\ln(1 + K_sT_s)$, where $K = 1/\ln(2)$ and $K_s = (8B_sR_mV_m/c\lambda)$. We illustrate the analytical concave nature of the proposed sensing measure in Fig. 2, for different values of R_m and V_m.

B. Communication Model

In this subsection, we discuss the communication aspects of the V2V ISAC system. Vehicle **A** is assumed to communicate with vehicle **B** over a Rayleigh fading channel [1], with the corresponding achievable data rate given as

$$R_c = \frac{B_c}{\ln 2}\ln\left(1 + \frac{|h|^2P_{Tc}}{N_0B_cR^2}\right). \tag{4}$$

Here, B_c, $g = |h|^2$, P_{Tc}, and N_0 denote the communication bandwidth, channel gain, communication transmit power, and noise power spectral density, respectively. With the wireless channel between **A** and **B** being Rayleigh distributed, the corresponding channel gain is exponentially distributed with unit mean, i.e., $g = |h|^2 \sim \exp(1)$. The data rate expression can be expressed as $R_c = B_cK\ln(K_c)$, with $K = 1/\ln 2$ and $K_c = (1 + gP_{Tc}/N_0B_cR^2)$. It may be noted that the term $(gP_{Tc}/N_0B_cR^2)$ represents the communication signal-to-noise ratio (SNR) at the receiver.

In this work, we assume that the communication operation follows the target sensing operation, i.e., the ISAC framework involves vehicle **A** first sensing **B** followed by communication within the total frame duration T. Hence, the total data that can be transferred from **A** to **B** is given by $D = T_cR_c$ bits, with T_c being the communication time duration.

III. OPTIMAL TIME PARTITIONING-BASED ISAC FRAMEWORK

In this section we formulate the OTP problem by first presenting the performance guarantees for the sensing and communication operations. Then we derive the optimal solution of the OTP problem and discuss the analytical insights.

A. Performance Measures

To ensure radar sensing performance in terms of false alarm rate and detection probability, the SNR of the received echo of an FMCW radar must be considered. For an FMCW radar, echo SNR is defined as

$$SNR_s = \left(\frac{\sigma P_{Ts}G^2\lambda^2T_s}{(4\pi)^3R^4kT_{temp}B_s}\right), \tag{5}$$

where σ is radar cross section (RCS) of the target, P_{Ts} is the transmit power of each antenna element of the radar, G is antenna gain (assumed equal for transmit and receive antenna), k is the Boltzmann constant, and T_{temp} is the operating temperature of the radar.

Let SNR_{req} be the required echo SNR to achieve a given false alarm and detection probability. Following this, for the desired maximum detection range R_m and the minimum RCS requirement σ_{min}, the sensing time T_s should be

$$T_s \geq \left(\frac{SNR_{req}(4\pi)^3R_m^4kT_{temp}B_s}{\sigma_{min}P_{Ts}G^2\lambda^2}\right). \tag{6}$$

Using the above relation, we can guarantee optimal radar sensing performance in terms of range and velocity detection, as well as false alarm and detection probability as

$$T_s \geq \max\left\{Nt_0, \left(\frac{SNR_{req}(4\pi)^3R_m^4kT_{temp}B_s}{\sigma P_{Ts}G^2\lambda^2}\right)\right\}. \tag{7}$$

Furthermore, the communication QoS is defined with respect to the communication throughput achieved through the framework. Mathematically, $T_cR_c \geq \alpha$, where α denotes the minimum data required to be transmitted in the V2V ISAC framework. In the next subsection, we discuss the optimal time partitioning formulation and solution.

B. OTP Problem Formulation and Solution

A sensing performance-guaranteed time partitioning optimization problem for the platooning scenario shown in Fig. 1 can be formulated by considering the total capacity of sensing, communication and timing constraints to obtain an optimal time allocation strategy. The proposed formulation is given below.

$$\begin{aligned} P1 :& \max_{T_s} \; K\ln(1 + K_sT_s) \\ s.t., \; C_1 :& \; T_s \geq \tau \\ C_2 :& \; T_cB_cK\ln K_c = (T - T_s)B_cK\ln K_c \geq \alpha, \end{aligned} \tag{8}$$

where $\tau = \max\left\{Nt_0, \left(\frac{SNR_{req}(4\pi)^3 R^4 k T_{temp} B_s}{\sigma P_{Ts} G^2 \lambda^2}\right)\right\}$.

Theorem 1. *The optimal sensing and communication time duration, considering the sensing and communication performance guarantees, is given as*

$$T_s^* = \begin{cases} \tau, & \text{if } \alpha = (T-\tau)B_c K \ln K_c \\ \left(\frac{TK_s B_c K \ln K_c + B_c K \ln K_c - K_s \alpha}{K_s B_c K \ln K_c}\right) - \frac{1}{K_s}, & \text{if } \alpha < (T-\tau)B_c K \ln K_c, \end{cases} \tag{9}$$

and $T_c^* = T - T_s^*$.

Proof. The objective function in (8) is observed to be concave while the constraints are affine. The Lagrangian of P1 is defined as,

$$\mathcal{L}(T_s, \gamma, \beta) = K \ln(1 + K_s T_s) + \gamma(T_s - \tau) + \beta\left((T - T_s)B_c K \ln K_c - \alpha\right). \tag{10}$$

Solving $\partial\mathcal{L}/\partial T_s = 0$, we can obtain

$$\frac{KK_s}{1 + K_s T_s} + \gamma - \beta B_c K \ln K_c = 0$$
$$\text{resulting in, } T_s = \frac{K}{(\beta B_c K \ln K_c - \gamma)} - \frac{1}{K_s}. \tag{11}$$

Next, we form the dual by substituting the primal solution (11) in (10). The resulting dual is given as

$$\mathcal{G}(\gamma, \beta) = K \ln\left(\frac{KK_s}{\beta B_c K \ln K_c - \gamma}\right) + \frac{\gamma K}{\beta B_c K \ln K_c - \gamma} - \frac{\gamma}{K_s} - \gamma\tau + \beta T B_c K \ln K_c - \frac{\beta B_c K \ln K}{\beta B_c K \ln K_c - \gamma} + \frac{\beta B_c K \ln K_c}{K_s} - \beta\alpha. \tag{12}$$

Solving $\partial\mathcal{G}/\partial\gamma = 0$ and substituting in (11), we obtain

$$\beta B_c K \ln K_c - \gamma = \frac{KK_s}{1 + K_s \tau},$$
$$\text{resulting in, } T_s = \tau. \tag{13}$$

Solving $\partial\mathcal{G}/\partial\beta = 0$, and substituting in (11), we get

$$\beta B_c K \ln K_c - \gamma = \frac{B_c K K K_s \ln K_c}{T B_c K K_s \ln K_c + B_c K \ln K_c - K_s \alpha},$$
$$\text{resulting in, } T_s = \left(\frac{TK_s B_c K \ln K_c + B_c K \ln K_c - K_s \alpha}{B_c K K_s \ln K_c}\right) - \frac{1}{K_s}. \tag{14}$$

Analyzing the constraints C_1 and C_2 of the primal problem in P1, we observe that $T_s \geq \tau$ and $T_s \leq T - \alpha/(B_c K \ln K_c)$. Hence the feasible region for optimal T_s is

$$\tau \leq T_s \leq T - \frac{\alpha}{B_c K \ln K_c}. \tag{15}$$

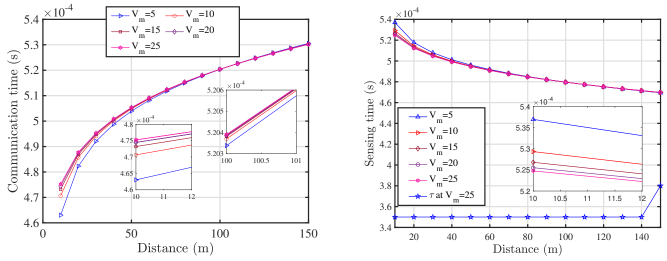
Using the lower and upper bounds in (15), we obtain

$$\alpha \leq (T - \tau)B_c K \ln K_c. \tag{16}$$

Note that (16) shows the coupling between the sensing and communication performance guarantees. Using the inference of (15), the dual solutions in (13) and (14) are substituted in the primal solution of (11) resulting in

$$T_s^* = \begin{cases} \tau, & \text{if } \alpha = (T-\tau)B_c K \ln K_c \\ \frac{TK_s B_c K \ln K_c + B_c K \ln K_c - K_s \alpha}{K_s B_c K \ln K_c} - \frac{1}{K_s}, & \text{if } \alpha < (T-\tau)B_c K \ln K_c. \end{cases} \tag{17}$$

□



(a) (b)

Fig. 3: Variation of optimal (a) communication and (b) sensing duration with distance for different velocities (in m/s).

Corollary 1.1. *The maximum amount data that can be communicated per frame via an ISAC system, is a function of the sensing performance guarantee τ in addition to the communication design parameters, i.e., B_c and K_c, and is given by*

$$\alpha \leq (T - \tau)B_c K \ln K_c. \tag{18}$$

Proof. The proof to Corollary 1.1 follows from the proof to Theorem 1 through (15) and (16). □

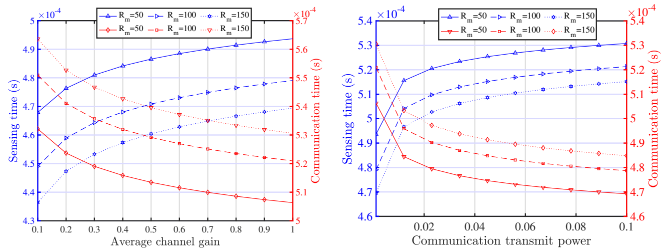
Here $\alpha \leq (T-\tau)B_c K \ln K_c$ represents the maximum amount of data that can be transferred per frame in a V2V ISAC framework as a function of the sensing and communication design parameters, i.e., τ, T, B_c, and K_c.

IV. PERFORMANCE EVALUATION

In this section, we present simulation results based on the proposed OTP-based ISAC framework and discuss inferences and observations based on these results. The simulation parameters for sensing [12] and communication are as follows: $T = 1$ ms, $P_{Tc} = 1$ mW, $P_{Ts} = 15$ mW, $\sigma = 1$ m^2, $G = 8$ dB, $B_s = 240$ MHz, $B_c = 180$ kHz, $f_r = 77$ GHz, $SNR_{req} = 15$ dB, $\alpha = 1.5\times10^3$ bits/frame, and $T_{temp} = 300$ K.

Fig. 3 illustrates the variation in optimal sensing and communication duration with respect to distance R for various platooning velocities. The distance R is varied from 10 m to 150 m considering a medium-range radar-based ISAC system. It can be inferred from Fig. 3(a) that the optimal communication time increases with distance, as well as with increasing velocity for a fixed distance, to achieve a given data rate. Complimentary to this, the optimal sensing time computed using the OTP-based ISAC framework decreases with distance R as seen in Fig. 3(b). However, it is noted that the optimal sensing time is greater than the theoretical threshold τ, thus guaranteeing sensing performance for the V2V ISAC system.

Fig. 4 shows the variation of optimal sensing and communication duration for varying average channel gain and communication transmit power for different target distances. It is observed from Fig. 4(a) that the optimal communication time decreases with increasing average channel gain. This is attributed to the fact that higher average channel gain indicates a better wireless communication link due to reduced fading, thus requiring less time to communicate the data. On the other



(a) (b)

Fig. 4: Illustration of adaptive nature of the proposed OTP framework; variation of sensing and communication time duration with (a) average channel gain and (b) communication transmit power.

hand, the optimal sensing time is observed to increase with the channel gain. It can be further inferred from Figs. 4(a) and 4(b) that the sensing duration decreases with increasing distance, which is consistent with the variation of sensing time shown in Fig. 3(b). A similar trend can be observed for communication time, which increases with the transmission distance R.

From Fig. 4(b), it is observed that at lower transmission power levels, higher communication time duration is required to meet the desired communication QoS. This is because, for a given amount of data, the communication power and communication time are inversely related resulting in reduced time with increasing power. In contrast, the sensing duration increases to support communication QoS while satisfying the constraint C_1. Figs. 4(a) and 4(b) demonstrate the adaptive nature of the proposed OTP framework, wherein the sensing and communication operations compliment each other's performance guarantees.

Fig. 5 shows the variation of communication throughput in bits/frame with respect to distance for different channel gains. The proposed OTP framework is compared with an ISAC system considering equal time partitioning (ETP). In general, throughput is observed to decrease with distance. However, it is notable that the throughput still satisfies the communication QoS at all distances. It is observed that with poor channel gain ($g = 0.1,\ 0.5$) the proposed OTP framework achieves a significant gain, up to 12.6%, over the ETP framework. However, for distances $R < 30$ m, throughput with the OTP framework is marginally lower than the ETP framework when $g = 1$. This is because, at shorter distances the optimal communication time computed via the OTP framework to satisfy the QoS is lower, thereby resulting in lower throughput with respect to that in the ETP framework. However, at increased distance with $g = 1$, the OTP framework achieves a gain up to 6.1%, thus demonstrating the merit of the proposed OTP-based ISAC framework.

V. Conclusion

In this paper, an optimal time partitioning (OTP) framework for V2V ISAC systems has been presented. A novel radar sensing measure as a function of maximum detectable range and velocity has been proposed. Constrained by sensing and communication performance guarantees, the optimal duration for sensing and communication has been derived. The proposed OTP framework aids in developing insight into the maximum achievable communication throughput as a function of desired sensing performance. The framework is useful in studying the trade-offs between sensing and communication design parameters towards developing optimal ISAC systems.

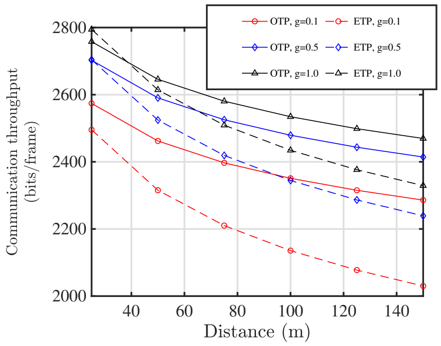


Fig. 5: Comparison of communication throughput variation with distance for the proposed OTP (i.e., $T_c = T_c^*$) and conventional ETP (i.e., $T_c = 0.5T$) frameworks.

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