Fast Transmission of Massive Concurrent Alarm Messages in LoRaWAN

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ABSTRACT

In the context of the Factories at Major Accident Risk (FMAR), we consider a scenario consisting of multiple sensor nodes that detect dangerous conditions and raise alarms over a LoRaWAN network. Upon event detection, a large number of nodes try to transmit concurrent alarm messages and the reception of at least one message is sufficient for the central server to react. We propose a scheme in which nodes operate in a slotted-time mode after the detection of the triggering event and they can only transmit one packet in a randomly chosen slot. The choice of the transmission slot follows a specific probability distribution that maximizes the probability of successful reception of at least one packet subject to real-time latency constraints. We provide an optimization framework to find the optimal distribution for choosing a transmission slot. We validate the proposed scheme by simulations and provide numerical results to compare the performance for three different slot choice distributions: i) uniform, ii) the distribution used in the Sift protocol [8], and iii) the proposed optimal distribution. The results show that the proposed optimal distribution leads to much better probability of successful packet delivery than other distributions.

CCS CONCEPTS

• **Networks → Network performance modeling**; *Very long-range networks*; *Sensor networks.*

KEYWORDS

LoRaWAN, Cyber-Physical Systems, Industrial IoT, Event-driven Transmissions, Concurrent Transmissions, Probability of Success

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1 INTRODUCTION

Smart Industry or Industry 4.0 have brought significant advancements in automation, data analytics, and connectivity to industrial processes. They also raise new safety and reliability challenges that need to be addressed both in terms of communication requirements and machine operability. We consider a scenario related to the Factories at Major Accident Risk (FMAR) [7] consisting of multiple sensor nodes that detect residual combustible gases, toxic gases, and reduced oxygen concentrations, and raise alarms to avoid fires or explosions involving flammable gas leakages, or prevent accidents. In such an environment, when a dangerous situation is detected by sensor nodes, they need to send alarm messages as quickly as possible to a central server that may take appropriate actions upon their reception. We assume that sensor nodes use the Long Range (LoRa®) wireless technology [2] and the Long Range Wide Area Network (LoRaWAN®)[3] communication protocol. We consider Class A sensor nodes that access the channel using the unslotted ALOHA protocol [1, 6]: a device wakes up and can send a packet at any instant on a chosen radio channel, provided its duty cycle follows the frequency band regulations (typically 1 % in the 868 MHz band under EU regulations). One or several gateways may receive the packet and forward it to network and application servers (the central control server in our scenario).

Detecting potentially dangerous events and event-driven message transmissions in an industrial environment is much different from the typical data collection in LoRa networks and raises an interesting research question. When an anomaly or a dangerous event is detected, many sensors will try to send concurrent alarm messages and the reception of at least one message is sufficient for the central server to react. It is a kind of the worst case scenario for the ALOHA access method—a large number of nodes trying to transmit simultaneously, which results in collisions and failed receptions. So, the problem that we address is to find the best strategy of the sensors for successful transmission of at least one message under strict real-time constraints. The objective of this paper is to design a protocol followed by sensor nodes that guarantees with a very high probability the delivery of at least one packet to the central server in a short time interval.

The paper is organized as follows. Section 2 briefly recalls related work. We present an optimization framework for maximizing successful packet delivery considering latency constraints in Section 3.

Section 4 validates the proposed scheme by comparing simulation and analytical results. Finally, Section 5 concludes the paper.

2 RELATED WORK

Only few authors addressed the problematic of detecting potentially dangerous events and event-driven message transmissions in an industrial environment in ALOHA-type of networks. The access method designed by Tay et al. [8] is one of only few proposals that address the challenge of event-driven scenarios in wireless networks with spatially correlated contention: multiple nodes in the same environment detect an event and need to transmit messages at the same time. The authors proposed a clever randomized non-persistent carrier-sense multiple-access protocol (CSMA) that departs from previous approaches by using a fixed-size contention window with multiple mini-slots and a carefully designed non-uniform probability distribution for transmissions within each mini-slot of the window. Assuming that a packet is much longer than the contention window and that any node can listen to the channel to check whether the channel is busy or not, no more than one packet is transmitted in the contention window; then, the proposed non-uniform distribution turns out to be optimal in terms of minimizing latency while maximizing the probability of successful delivery. In particular, the authors introduced two distributions: i) CSMA/p* that requires perfect knowledge of the total number contenders and ii) Sift, oblivious to the total number of contenders, that approximates the optimal distribution. In our proposed scheme, we adopt a similar approach based on a specific probability distribution for transmissions but we adapt the distribution to LoRaWAN, which results in better performance than Sift.

3 ANALYTICAL MODEL OF EVENT-DRIVEN TRANSMISSIONS

In this section, we derive an analytical model for Packet Delivery Ratio (PDR) in the event-driven scenario and find the optimal distribution for choosing a transmission slot that maximizes successful packet delivery under latency constraints.

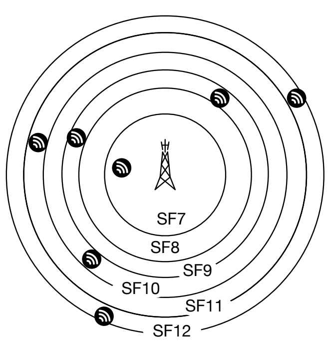

Figure 1: Rings of devices having the same Spreading Factor (*SF*)

We assume a LoRaWAN single-star topology in which a gateway is in the middle of an area to be monitored. Sensor nodes are randomly distributed in this area according to a distribution e.g., a homogeneous Poisson process resulting in uniform coverage of the area. We also assume that the monitored event is detected by all nodes simultaneously, which corresponds to the worst case since the probability of collisions is the highest. According to the LoRaWAN protocol, each node configures the Spreading Factor (SF) based on the level of the signal received at the gateway, which results in the ring structure presented in Figure 1.

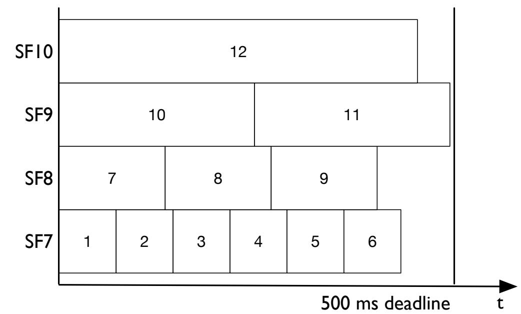

Figure 2: Possible transmissions for each SF under the constraint of the 500 ms deadline

We also adopt the same stringent requirements and constraints as in the previous case of the industrial environment [7]: a PDR greater than 99.9% and the end-to-end latency (the time interval for transmitting at least one alarm packet) shorter than 500 ms with the payload of 20 bytes. The requirements limit the use of SF to SF7-SF10 since the time-on-the-air for SF11 and SF12 exceeds the maximum delay constraint. The number of available transmission slots depends on SF as shown in Figure 2. We neglect collisions between devices transmitting at different SFs.

3.1 Analytical Evaluation of PDR

Let us assume that the node distribution in space follows a homogeneous Poisson process with density σ nodes/m^2. So, the number of nodes in a region of area A follows a Poisson distribution with probability:

$$Pr\left\{N(A) = n\right\} = \frac{(\sigma A)^n}{n!} e^{-\sigma A} \tag{1}$$

Consider a circular region of area A_t divided into K rings of area A_k, with $\sum_{k=1}^{K} A_k = A_t$. Devices in each region use SF$_k$ and have S_k available slots.

Let us now focus on evaluating the PDR for the k-th ring: a packet is considered to be correctly received if at least one of all transmitted packets is received. The number of nodes in ring k is denoted by $N(A_k)$ and they are assumed to transmit at the same time. We denote $P_k^{(M)}$ the probability of successful transmission in the k-th ring where M represents the total number of nodes involved in collision.

First, we derive the probability of successful transmission in the presence of noise $P_k^{(1)}$ when there is no collision. If the noise variance is W, the minimum Signal to Noise Ratio (SNR) is $\gamma_{th}(k)$, the received power[1] is $P_{\text{rx}}(k)$, we have under the Rayleigh fading

[1]We assume that the receiving power is the same for all devices in a ring.

assumption:

$$P_k^{(1)} = e^{-W\gamma_{th}(k)/P_{\rm rx}(k)} \quad (2)$$

Then, we evaluate the capture probability given M colliding nodes in slot l, which corresponds to the probability that the power received by one node is $\bar{\gamma}_o$ dB higher than the sum of the powers received by the other nodes in the slot (i.e., the interference). Let us denote by $\gamma_o = 10^{\bar{\gamma}_o/10}$ the capturing threshold on a linear scale, with $\gamma_o \geq 1$.

For $M = 2$, we have only two packets interfering with each other, and for any of them, the random gain g_1 needs to both allow it to dominate noise and the other packet (received with gain g_2). Thus, as both frames are interchangeable, the probability of success in this case is (as in Eq. 12 in previous work [4]):

$$P_k^{(2)} = 2\ Pr\left\{g_1 > \frac{W\gamma_{th}(k)}{P_{rx}(k)} \cap g_1 > \gamma_o g_2\right\} \quad (3)$$

$$= 2\ \frac{P_k^{(1)}}{\gamma_o + 1}\left(1 + \gamma_o(1 - (P_k^{(1)})^{\frac{1}{\gamma_o}})\right) \quad (4)$$

For $M > 2$, we make a simplifying (and pessimistic) assumption that the probabilities of dominating noise and interference are independent. We denote $\bar{C}_{k,m}^{(M)}$ the event that the packet m of a slot in the ring k is not captured in the presence of M colliding packets. Thus, the probability that none of the M packets will be captured, with $M > 2$, can be computed as follows:

$$Q_k^{(M)} = Pr\left\{\bar{C}_{k,1}^{(M)}, \bar{C}_{k,2}^{(M)}, \ldots, \bar{C}_{k,M}^{(M)}\right\}$$
$$= \prod_{m=1}^{M} Pr\left\{\bar{C}_{k,m}^{(M)} | \bar{C}_{k,1}^{(M)}, \ldots, \bar{C}_{k,m-1}^{(M)}\right\} \quad (5)$$

We can derive a simple lower bound from the following observation: the conditional probability that packet m is not captured when none of the packets q with $q < m$ are captured, is smaller than the unconditional probability $\bar{C}_{k,m}^{(M)}$. Hence, we can introduce the upper bound:

$$\hat{Q}_k^{(M)} = \prod_{m=1}^{M} Pr\left\{\bar{C}_{k,m}^{(M)}\right\}, \quad (6)$$

where $Q_k^{(M)} \leq \hat{Q}_k^{(M)}$.

For the evaluation of $Pr\left\{\bar{C}_{k,m}^{(M)}\right\}$, we denote by $x_1, x_2, \ldots, x_M$ the fading terms of the M colliding nodes. The probability that the first packet is captured can be computed as follows:

$$H_{k,1} = \int_0^\infty e^{-x_2} \ldots \int_0^\infty e^{-x_M} e^{-\gamma_o \sum_{m=2}^{M} x_m} dx_2 \ldots dx_M$$
$$= \left(\frac{1}{1+\gamma_o}\right)^{M-1} \quad (7)$$

For symmetry, we have $H_{k,m} = H_{k,1}$, $m = 2, \ldots, M$ and thus:

$$\hat{Q}_k^{(M)} = \left[1 - \left(\frac{1}{1+\gamma_o}\right)^{M-1}\right]^M \quad (8)$$

Assuming that each node of the k-th ring selects the slot randomly according to probabilities $\mathbf{P}_k = \left\{P_{k,1}, \ldots, P_{k,S_k}\right\}$, we can notice that the number of nodes selecting slot l in ring k follows a Poisson distribution with factor $P_{k,l}\sigma$. Let us introduce:

$$P_{k,M,l} = \frac{\left(P_{k,l}\sigma A_k\right)^M}{M!} e^{-P_{k,l}\sigma A_k} \quad (9)$$

the probability of M colliding packets in slot l of ring k. Thus, the probability of successful transmission for slot l in ring k can be bounded below by:

$$R_{l,k} = P_{k,1,l}P_k^{(1)} + P_{k,2,l}P_k^{(2)}$$
$$+ P_k^{(1)} \sum_{M=3}^{\infty} P_{k,M,l}\left(1 - \hat{Q}_k^{(M)}\right) \quad (10)$$

and finally, we obtain the following expression for PDR:

$$PDR \geq 1 - \prod_{k=1}^{K} \prod_{l=1}^{S_k} (1 - R_{l,k}) \quad (11)$$

3.2 Optimization of the Slot Probability

We can notice that $R_{l,k}$ in Eq. (10) is independent of $P_{j,k}$ with $j \neq l$. Accordingly, the PDR bound Eq. (11) can be maximized separately for each variable $P_{k,l}$, so we can rewrite Eq. (10) as follows:

$$R_k(P_k) = P_{k,1}(P_k)P_k^{(1)} + P_{k,2}(P_k)P_k^{(2)}$$
$$+ P_k^{(1)} \sum_{M=3}^{\infty} P_{k,M}(P_k)\left(1 - \hat{Q}_k^{(M)}\right), \quad (12)$$

where $P_{k,M}(P_k) = \frac{(P_k \sigma A_k)^M}{M!} e^{-P_k \sigma A_k}$. Then, the optimization problem can be formulated as:

$$\mathbf{P} = \arg\min_{\mathbf{P}} \prod_{k=1}^{K} \left[1 - R_k(P_k)\right]^{S_k}$$
$$\text{s.t.:} \quad (13)$$
$$S_k P_k \leq 1$$
$$P_k \geq 0,$$

where $\mathbf{P} = \{P_1, \ldots, P_K\}$. Finally, noting that the problem in Eq. (13) is separable in P_k, we can formulate the single variable problem:

$$P_k^* = \arg\max_{\mathrm{P_k}} R_k(P_k)$$
$$\text{s.t.:} \quad (14)$$
$$S_k P_k \leq 1$$
$$P_k \geq 0$$

The problem in Eq. (14) can be solved through an exhaustive search by sampling the variable P_k in the interval $[0, 1/S_k]$. We can perform the optimization ring by ring to find a unique solution P_k^* for each ring.

3.3 Statistical Knowledge of σ

To be more general, we consider a discrete model for the node density and assume that σ takes values in a discrete set $\sigma = \{\sigma_1, \sigma_2, \ldots, \sigma_\Delta\}$ with probabilities $Q_\delta = \Pr\{\sigma = \sigma_\delta\}$. Thus, if we condition the analysis on a given σ, the same considerations and derivations apply as before, and in particular, the conditional probability of successful transmission in ring k can be bounded below by:

$$R_k(P_k, \sigma) = P_{k,1}(P_k, \sigma)P_k^{(1)} + P_{k,2}(P_k, \sigma)P_k^{(2)} + P_k^{(1)} \sum_{M=3}^{\infty} P_{k,M}(P_k, \sigma)\left(1 - \hat{Q}_k^{(M)}\right), \quad (15)$$

where $P_{k,M}(P_k, \sigma) = \frac{(P_k \sigma A_k)^M}{M!} e^{-P_k \sigma A_k}$. Then, we can formulate the optimization problem as follows:

$$\mathbf{P} = \arg\min_{\mathbf{P}} \sum_{\delta=1}^{\Delta} \prod_{k=1}^{K} [1 - R_k(P_k, \sigma_\delta)]^{S_k} Q_\delta \quad \text{s.t.:} \quad S_k P_k \le 1, \quad P_k \ge 0 \quad (16)$$

However, the problem cannot be separated as before, and the solution of the problem in Eq. (16) is complex because the objective function is not convex. To overcome this difficulty, we assume that the optimal P_k satisfy a proportional relation, i.e., $P_k^* S_k = S_j P_j^*$. Note that this relation holds naturally when the optimal solution is $P_k^* = 1/S_k$, i.e., when each node transmits with probability one. Conversely, if $P_k^* < 1/S_k$, the approximation is not guaranteed to be optimal, therefore, we can consider the proposed approach as a sub-optimal solution to the problem in Eq. (16). We evaluate the validity of the considered approximation in the next section.

Thus, we can reformulate the problem as a single-variable problem in the generic variable P_k as follows:

$$\mathbf{P} = \arg\min_{\mathbf{P}} \sum_{\delta=1}^{\Delta} \prod_{j=1}^{K} \left[1 - R_j\left(\frac{S_k P_k}{S_j}, \sigma_\delta\right)\right]^{S_j} Q_\delta \quad \text{s.t.:} \quad S_k P_k \le 1, \quad P_k \ge 0 \quad (17)$$

and we can set $P_j = \frac{S_k P_k}{S_j}$ for $j \ne k$. As before, the problem in Eq. (16) can be solved by an exhaustive search, sampling the variable P_k in the interval $[0, 1/S_k]$.

4 VALIDATION

In this section, we validate the theoretical analysis by comparing the numerical results with the outcome of a realistic simulator.

4.1 Simulation Set-up

We have adapted a discrete event simulator written in Python [4, 5] to the case of event-driven concurrent transmissions where the packet generation follows a homogeneous Poisson process with aligned start times and the performance metric focuses on the reception of a single frame. We simulate a LoRaWAN network with a radius of 2500 m with a single gateway and a single channel. The bandwidth and transmission power are set to 125 kHz and 14 dBm respectively. Moreover, simulator considers the Okumura-Hata channel model with the physical capture model (threshold of 1 dB) taking into account the Rayleigh fading.

We focus on two different cases for generating nodes in the environment. In the first case, denoted **Case 1**, nodes are generated according to a homogeneous Poisson process with a density σ, while in the second case, denoted **Case 2**, we generate nodes according to a uniform distribution in an interval $[M_{min}, M_{max}]$ as in the analysis in Section 3.3 under conditions $\sigma_1 = M_{min}/A_t$, $\sigma_\Delta = M_{max}/A_t$, $D = M_{max} - M_{min}$, and $Q_\delta = 1/D$. Note that in this second case, the theoretical analysis assumes that the density of nodes is uniform, while the simulations suppose that the number of nodes is uniform. Thus, there is a discrepancy, but it does not affect the validity of the analysis, as we show below. In other words, the conditional Poisson model is sufficiently general to capture the essence of more general types of distributions for which the analysis would be more complex. All nodes transmit synchronously during the slot selected from a given slot-selection distribution.

4.2 Numerical Results

In this section, we report on the main results obtained with simulations and the theoretical analysis. We assess the performance in terms of achieved PDR as a function of the average number of nodes M.

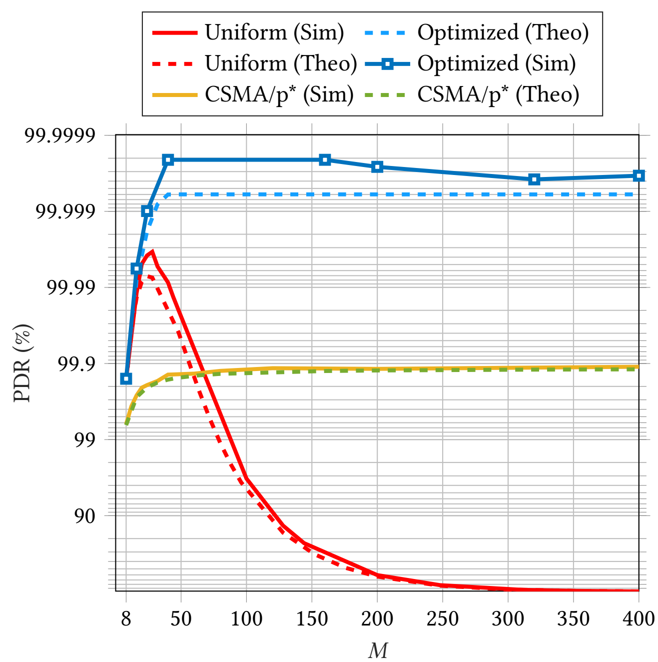

Figure 3: Case 1: PDR for the known number of nodes M

Case 1:Figure 3 shows the performance of three slot selection distributions: i) uniform (i.e., $P_k = 1/S_k$), ii) the CSMA/p* distribution [8] that assumes perfect knowledge of the number of nodes, and iii) the proposed optimized distribution. The figure clearly illustrates the deterioration of the performance for the uniform distribution as the number of nodes increases, mainly due to collisions. In contrast, the optimal CSMA/p* algorithm [8] exhibits promising results even when the number of nodes significantly increases. As discussed in Section 2, CSMA/p* is optimal under the assumption that the packet

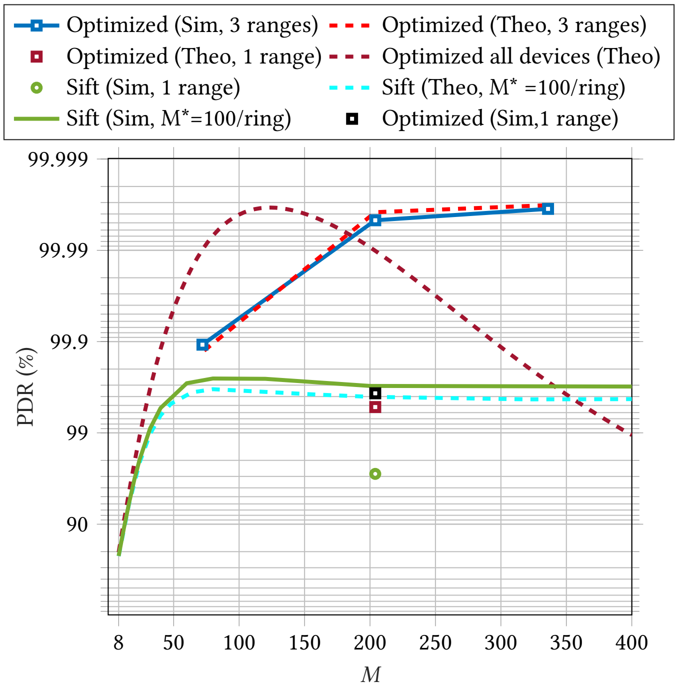

Figure 4: Case 2: PDR for the known M distribution (uniformly distributed in the $[M_{min}, M_{max}]$ interval)

to transmit is much longer than the contention window, and thus, it is not surprising that the proposed solution performs significantly better in the considered scenario. In summary, the superiority of our optimized solution highlights the effectiveness of our approach in improving reliability and addressing the challenges associated with collisions for the considered FMAR scenario when the density of nodes is known.

Case 2: Figure 4 shows the performance of the optimal distribution when nodes are uniformly distributed over different ranges—we consider four ranges for the interval $[M_{min}, M_{max}]$: $[8, 138]$, $[139, 269]$ and $[270, 400]$ as well as one range of $[8, 400]$.

In all cases, the points on the x-axis correspond to the average of the corresponding interval. As the first observation, we can notice that the analysis matches the simulations almost perfectly and for this reason the two curves almost overlap. Moreover, it is worth noting that the performance deteriorates with respect to **Case 1**, since in this case, we have less a priori information about the number of nodes in the network. This effect is, of course, more pronounced when we consider a single range. In the comparison, we give the results for the Sift distribution [8] that does not rely on the knowledge of the number of nodes, but approximates the distribution for an arbitrary number of nodes by considering a prespecified maximum number of average concurrent nodes, denoted by M^*. For our analysis, we set M^* to 100 per ring, which results in the total number of 400 nodes in the network. Interestingly, the Sift distribution obtains good results for a larger number of nodes. However, its performance still deteriorates when the number of nodes exceeds this value. It is important to note that our optimal solution outperforms Sift, especially when considering a single interval $[8, 400]$.

The figure also shows the performance of the two considered approaches for each possible value of the average number of nodes M. We can clearly see that the proposed optimized approach always performs better than Sift, except when the number of nodes approaches 400, the maximum number assumed by Sift. Obviously, the performance in this case is much worse than in **Case 1**, since we lack detailed information about nodes apart from their distribution and range.

In summary, the selection of a particular approach and the use of probability distributions depend on the specific use case and the service requirements at hand.

5 CONCLUSIONS

This paper considers an industrial use case of LoRaWAN networks consisting of simultaneous transmission of alert messages upon the detection of a dangerous event. The problem boils down to optimizing the access probability in each slot defined relative to the trigger event. We show that simple uniformly distributed transmissions across all slots is not the best approach, and that, it is better to follow a specific slot distribution. The main contribution of the paper is the derivation of a theoretical model for event-driven simultaneous transmissions in LoRaWAN. We use the model to compute the access probability that maximizes successful alarm message reception for a given node density. Since the number of nodes attempting transmissions may be unknown, we also show that we can find a transmission probability that provides an acceptable level of alarm message reception over a wide range of node densities. Finally, we show that our uniform slot selection distribution outperforms the exponentially shaped Sift distribution.

6 ACKNOWLEDGMENTS

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