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Enhancing Reliability and Energy Efficiency for Industrial IoT Using IRSA-PSO

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ABSTRACT

This paper introduces an Irregular Repetition Slotted ALOHA (IRSA) with Particle Swarm Optimization (PSO) approach for improving energy efficiency in Industrial Internet of Things (IIoT) networks. The proposed approach combines the simplicity and scalability of IRSA with the optimization capabilities of PSO to enhance network performance. By optimizing the repetition patterns and slot allocations, the IRSA-PSO approach minimizes collisions and improves the overall system efficiency. Through extensive simulations, we demonstrate that the proposed approach outperforms existing protocols in terms of achieving the desired error rate while reducing energy consumption. This contribution addresses the challenges of error rate and energy efficiency in IIoT networks, providing a valuable framework for designing efficient and reliable communication protocols in IIoT applications.

Key Words : Particle swarm optimization, irregular repetition slotted ALOHA, uplink, IoT, energy efficiency, reliability, optimization, Industrial IoT

Ⅰ. Introduction

With the rapid growth of Industrial Internet of Things (IIoT) networks, there is a need for efficient communication protocols that can achieve low error rates while optimizing energy consumption[1-3]. This paper presents a novel approach that combines Irregular Repetition Slotted ALOHA (IRSA) with Particle Swarm Optimization (PSO) to address these challenges[4-6]. IRSA is a random-access protocol known for its simplicity and scalability, while PSO is a population-based optimization algorithm inspired by social behavior. Reliability and low latency are key considerations in wireless communications, such as Ultra Reliable and Low Latency Communications (URLLC) in the 5G system[7-11]. Therefore, these aspects are also important in IIoT networks[12,13]. IRSA can be considered as a solution for these networks. With IRSA, grant-free uplink transmission can be implemented[14,15], and packet collisions can be recovered. Thus, in IIoT networks that require low latency and high reliability, IRSA can be a suitable solution. However, IRSA's repeated transmission can result in high energy consumption, making it less suitable for IIoT devices with limited power sources, such as battery-powered devices. Most research on IRSA has focused on reliability and throughput. [16] adopts a deep reinforcement learning approach to find the degree distribution that achieves high throughput. [17] introduces IRSA with priority and evaluates it

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in terms of throughput and channel usage. [18] proposes and evaluates non-orthogonal multiple access (NOMA) based IRSA in terms of throughput and packet loss rate. [19] proposes adaptive traffic load in the IRSA-NOMA system to satisfy the priority of emergency devices in terms of throughput. However, previous research has not considered scenarios with limited power sources, such as IIoT networks. To address this, PSO can optimize the repetition factor to strike a balance between reliability and power consumption in this study. The proposed approach aims to achieve a target error rate while enhancing energy efficiency in IIoT networks. The paper introduces the concept of IRSA, where devices transmit packets using random time slots and repetition patterns. By incorporating PSO into IRSA, the algorithm optimizes the selection of repetition patterns and slot allocations to minimize collisions and improve overall network performance. PSO guides the search process by leveraging the collective intelligence of particles to converge towards optimal parameter configurations that satisfy the target collision rate requirement. Evaluations are conducted to assess the proposed approach's performance in terms of collision rate and energy efficiency. The results demonstrate that the IRSA-PSO approach outperforms traditional IRSA and other existing protocols in achieving the desired collision rate while reducing energy consumption. Furthermore, the approach exhibits robustness to varying network conditions, including node density and traffic load. These findings highlight the potential of the IRSA-PSO approach as a solution for IIoT networks. By effectively balancing error rate and energy efficiency, the proposed approach enables reliable and energy-efficient communication in IIoT deployments. These results contribute to the advancement of wireless communication protocols, specifically targeting the unique challenges of IIoT networks.

Ⅱ. System Model

2.1 System description

In this study, we consider a grant-free uplink system in a IIoT network that requires reliable and

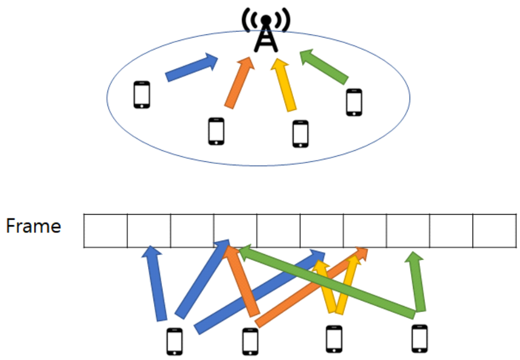

Fig. 1. System Model

energy efficient transmissions. To reduce the collision rate during uplink transmission, we adopt IRSA protocol, where each node transmits signals with irregular repetition. While this repetition can help reduce collisions, it also results in increased energy consumption. Since IoT networks aim for low energy consumption due to limited battery power, it is important to find a balance between collision rate and energy consumption. The system consists of a base station (BS) and nodes, as illustrated in Fig. 1. The BS receives uplink signals from the nodes, as described in Fig. 1. In this system model, only uplink signals from the nodes to the BS are considered for simplicity. These uplink nodes transmit irregular uplink signals within a frame following the IRSA protocol. Each arrow represents an uplink signal from each node to the BS. Since the system employs IRSA, uplink signals from a node are randomly retransmitted based on the repetition rate. These transmissions are organized into timeslots within a frame. Since there is no central timeslot allocation, collisions between transmissions from different nodes may occur. Nevertheless, in the absence of collisions for a transmitted signal, both the signal and its duplicates are canceled, contributing to the decoding of other signals originating from different nodes.

2.2 Irregular repetition slotted ALOHA

IRSA is an enhanced version of the traditional Slotted ALOHA protocol used in wireless communication systems[20]. ALOHA is a random-access protocol that allows multiple devices to share the same communication channel [21]. In the traditional Slotted ALOHA, time is divided into fixed time slots, and each device randomly chooses a slot to transmit its data. However, this can result in collisions and reduced efficiency. IRSA introduces irregular repetition to the Slotted ALOHA protocol to improve its performance. In IRSA, the time slots are not equally spaced, and devices have different probabilities of transmitting in each slot. This irregularity helps reduce collisions and improve the overall efficiency of the system. By strategically assigning different probabilities to time slots, IRSA aims to increase the chances of successful transmissions and minimize the occurrence of packet collisions. Fig. 2 illustrates the interference cancellation (IC) process of IRSA. We assume there are 4 uplink nodes and a frame consisting of 4 timeslots, and there is no decoding error if no collision appears. In the first phase of Fig. 2, the user denoted as B2 has uninterrupted uplink transmission in timeslot S2, allowing the decoding of B2's signals while canceling all other signals from B2. In the second phase, the signal of B1 in S1 is decoded without any collision, and all signals from B2 are canceled. The third phase shows that only signals from 2 users remain, and the signal of B3 in S3 is decoded while canceling all signals from B3. In the fourth phase, the signal of B4 is decoded, resulting in the successful decoding of all users' signals. According to Fig. 2, we can observe that duplicated transmissions can be canceled if only one transmission is collision-free. By iteratively identifying transmissions without collisions and canceling the duplicated ones, all signals can be successfully decoded. In this study, IRSA is used as the uplink transmission protocol to address the collision rate.

	S1(Timeslot)	S2(Timeslot)	S3(Timeslot)	S4(Timeslot)
B1(User1)	O		O	
B2(User2)	O	O		
B3(User3)			O	O
B4(User4)				O

	S1(Timeslot)	S2(Timeslot)	S3(Timeslot)	S4(Timeslot)
B1(User1)	O		O	
B2(User2)				
B3(User3)			O	O
B4(User4)				O

	S1(Timeslot)	S2(Timeslot)	S3(Timeslot)	S4(Timeslot)
B1(User1)				
B2(User2)				
B3(User3)			O	O
B4(User4)				O

	S1(Timeslot)	S2(Timeslot)	S3(Timeslot)	S4(Timeslot)
B1(User1)				
B2(User2)				
B3(User3)				
B4(User4)				O

Fig. 2. Interference cancellation procedure of IRSA

2.3 Particle swarm optimization

PSO is a computational optimization technique inspired by the social behavior of bird flocking or fish schooling. It is a population-based metaheuristic algorithm that can be used to solve optimization problems. In PSO, a population of candidate solutions, called particles, moves through the search space to find the optimal solution. Each particle represents a potential solution and has a position and velocity. The particles' movement is influenced by their own best-known position (individual best) and the best-known position among the entire population (global best) [3]. The algorithm starts by randomly initializing the particles within the search space. In each iteration, the particles adjust their velocities based on their current positions and the information from their personal and global best positions. The new velocities determine the direction and speed of movement. The particles then update their positions accordingly. This process continues iteratively until a stopping criterion is met, typically a maximum number of iterations or reaching a desired solution quality. PSO has been widely used for optimization problems in various domains, including engineering, finance, data mining, and machine learning. It is particularly suitable for problems with continuous search spaces and non-linear objective functions. By leveraging the collective intelligence of the particle swarm, PSO explores the search space efficiently and converges towards promising regions that may contain optimal solutions. In this study, PSO is used to find an optimized point between energy consumption and collision rate.

Ⅲ. Proposed Method

In this study, IRSA is adopted to address collisions caused by multiple uplink nodes, and PSO is employed to find an optimized point between energy consumption and collision rate. Before explaining the proposed method, we will discuss the transmission probability distribution of IRSA[2]. The nodes that transmit signals using IRSA follow a transmission probability distribution. This distribution can be expressed in terms of nodes and timeslots. The formulas are as follows:

$$\Lambda(x) = \sum_l \Lambda_l x^l, \quad \Psi(x) = \sum_l \Psi_l x^l. \tag{1}$$

Λ represents the degree distribution on the node side, Ψ represents the degree distribution on the timeslot side, l denotes the degree of collisions between transmissions. Using equation (1), we can derive the degree distribution from an edge perspective, which represents the probability that an edge belongs to a degree of l. The degree distribution from an edge perspective can also be expressed in terms of the node side and timeslot side. The formulas are as follows:

$$\lambda(x) = \sum_l \lambda_l x^{l-1}, \quad \rho(x) = \sum_l \rho_l x^{l-1}. \tag{2}$$

Based on (2), the probability q that a packet cannot be cancelled through its replicas is as follows:

$$q_{i+1} = \lambda\left(1 - e^{-q_i G \Lambda'(1)}\right), \quad q \in (0, 1]. \tag{3}$$

G represents the ratio m/n, which is the ratio between the number of nodes m and the number of timeslots n in the frame. Using (3), the collision rate can be estimated. Since the study aims to find the balanced point between power consumption and collision rate, the optimization of $\Lambda(x)$ in (1) is necessary using PSO.

The following equations describe the functioning of PSO:

$$x_i^{t+1} = x_i^t + v_i^{t+1}, \tag{3}$$

$$v_i^{t+1} = v_i^t + c_1\epsilon_1(g^* - x_i^t) + c_2\epsilon_2(x_i^* - x_i^t). \tag{4}$$

Equation (3) represents the position vector of a particle, which is considered Λ the distribution of node side in (1). Equation (4) represents the velocity vector that guides the particle's movement towards a near-optimal solution. The acceleration coefficients c_1 and c_2, as well as the random values ϵ_1 and ϵ_2, are involved in the velocity calculation. g^* denotes the swarm's best solution, while x_i^* represents the individual best solution of the particle. After obtaining the velocity v, it is added to the current position of the particle x_i^t using (3). The position of the particle x_i^t is then updated to x_i^{t+1}. This process of position update is iterated until the termination condition is met. Optimizing x_i^t implies optimizing the distribution of the node side Λ in (1). The optimization problem can be formulated as follows:

$$\begin{aligned} &\textit{Minimize} \ \ q_i = \lambda\left(1 - e^{-q_{i-1} G \Lambda'(1)}\right), \\ &\textit{Maximize} \ \ E = \frac{1}{\Lambda'(1)}, \\ &\textit{subject to} \quad q \in (0, 1], \\ &\quad i \le I, \\ &\quad q_I \le T. \end{aligned}$$

q should be minimized and kept below the target collision rate T after I iterations, while energy efficiency E should be maximized. Regarding energy efficiency, we assume that a single transmission without any repetition in a frame achieves 100% energy efficiency. Hence, nodes with fewer transmissions in a frame are considered to have higher energy efficiency. The fitness function must be configured to meet the target collision rate T and decrease the transmission repetition rate of IRSA. To address this problem, the fitness score f is defined as follows:

$$f = \begin{cases} \dfrac{100}{\Lambda'(1)}, & \textit{if} \ \ q_I \le T. \\ -10, & \textit{otherwise}. \end{cases}$$

Based on the fitness function, PSO optimizes the distribution Λ, which determines the repetition of node transmissions.

Ⅳ. Evaluation and Results

In this section, the collision rate and energy efficiency of IRSA-PSO are evaluated by comparing them with fixed distributions of IRSA. The evaluation parameters are described in Table 1. Firstly, the balanced point, which represents the result of PSO, is depicted by varying the number of users in Fig. 3. The number of users ranges from 5 to 7. The results demonstrate that IRSA-PSO achieves the target collision rate while reducing energy consumption. If the target collision rate was not met, the fitness score would be -10 points. If the target collision rate was achieved, a higher fitness score would indicate fewer repetitions, as fewer repetitions result in less energy consumption.

Based on the distributions determined by PSO in the results from Fig. 3, collision rates are evaluated for the cases of 5 users, 6 users, and 7 users. The collision rates of IRSA-PSO are compared with the predetermined distributions outlined in Table 1, as detailed in [4]. Fig. 4 illustrates that IRSA-PSO satisfies the target collision rate after 200 iterations of IC.

Similarly, Fig. 5 and Fig. 6 demonstrate that IRSA-PSO also meets the target collision rate after 200 IC iterations. The evaluation results for energy efficiency are presented in Table 2. IRSA-PSO

Table 1. Evaluation Parameters

IC iteration	200
Target collision rate	0.001
Frame size	10 timeslots
Number of particles	100
PSO iteration	150
Fixed Distribution 1	$\Lambda(x) = 0.5102x^2 + 0.4898x^4$
Fixed Distribution 2	$\Lambda(x) = 0.5631x^2 + 0.0.0436x^3 + 0.3933x^5$
Fixed Distribution 3	$\Lambda(x) = 0.5x^2 + 0.28x^3 + 0.22x^8$

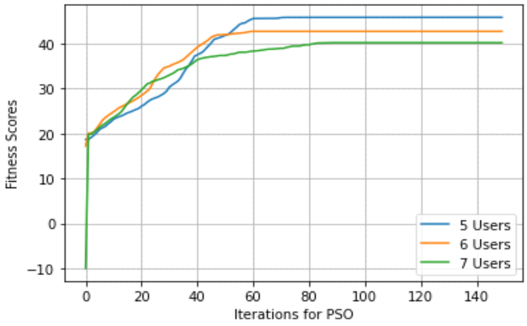

Fig. 3. Fitness score for IRSA-PSO

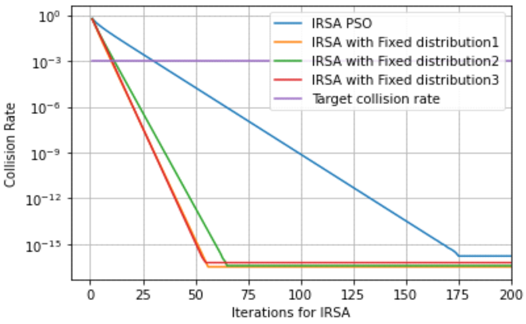

Fig. 4. Collision rate (5 users)

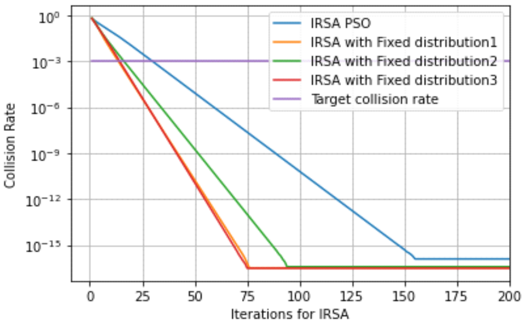

Fig. 5. Collision rate (6 users)

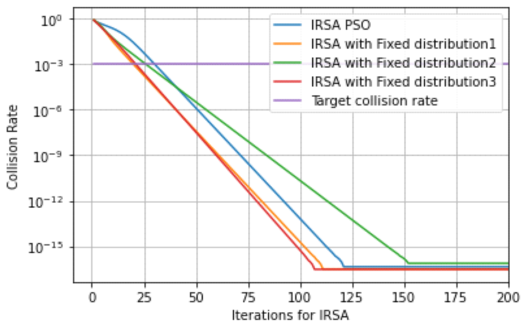

Fig. 6. Collision rate (7 users)

Table 2. Energy Efficiency

	5 Users	6 Users	7 Users
IRSA PSO	45.82%	42.69%	40.18%
Fixed Distribution 1	28.82%	28.82%	28.82%
Fixed Distribution 2	31.02%	31.02%	31.02%
Fixed Distribution 3	27.78%	27.78%	27.78%

demonstrates superior performance compared to the fixed distributions in terms of energy efficiency. This indicates that IRSA-PSO can effectively reduce energy consumption and can be considered as a viable solution for wireless IoT networks that demand high reliability despite limited power resources.

V. Conclusion

In this study, we proposed the integration of Irregular Repetition Slotted A LOHA (IRSA) with Particle Swarm Optimization (PSO) as a novel approach to address the challenges of Industrial Internet of Things (IIoT) networks. By considering the requirements of high reliability and low energy consumption in IIoT deployments, we aimed to strike a balance between these two factors. Through evaluations, we demonstrated that the IRSA-PSO approach achieves the desired reliability targets while improving energy efficiency. Our findings highlight the potential of the IRSA-PSO approach as a solution for wireless IoT networks. By effectively optimizing the distribution of node repetitions and transmission probabilities, we were able to satisfy the target collision rates and enhance energy efficiency of network performance. The results from our evaluation indicated that the IRSA-PSO approach outperformed fixed distribution schemes in terms of energy efficiency, demonstrating its effectiveness in achieving high reliability and energy efficiency. Looking ahead, further research can be conducted to explore additional optimization techniques, alternative protocols, and the integration of other emerging technologies. Additionally, investigating the scalability of the IRSA-PSO approach to larger IIoT networks and its compatibility with different IoT application domains would be valuable areas for future investigation. In conclusion, our study contributes to the advancement of wireless communication protocols specifically tailored to the unique challenges of IIoT networks. By combining the simplicity and scalability of IRSA with the optimization capabilities of PSO, we have provided a practical solution that enables reliable and energy-efficient communication in IIoT deployments. The proposed IRSA-PSO approach holds great promise for facilitating the widespread adoption and successful implementation of IIoT networks in various industries and domains.

References

[1] S. Madakam, R. Ramaswamy, and S. Tripathi, "Internet of things (IoT): A literature review," *J. Comput. and Commun.*, vol. 3, no. 5, pp. 164-173, 2015. (https://doi.org/10.4236/jcc.2015.35021)

[2] D.-S. Kim, T.-D. Hoa, and H.-T. Thien, "On the reliability of industrial internet of things from systematic perspectives: Evaluation approaches, challenges, and open issues," *IETE Tech. Rev.*, vol. 39, no. 6, pp. 1277-1308, 2022. (https://doi.org/10.1080/02564602.2022.2028586)

[3] N. B. Long, H. Tran-Dang, and D.-S. Kim, "Energy-aware real-time routing for large-scale industrial internet of things," *IEEE Internet of Things J.*, vol. 5, no. 3, pp. 2190-2199, 2018. (https://doi.org/10.1109/JIOT.2018.2827050)

[4] G. Liva, "Graph-based analysis and optimization of contention resolution diversity slotted ALOHA," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 477-487, 2011. (https://doi.org/10.1109/TCOMM.2010.120710.100054)

[5] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. ICNN'95*, pp. 1942-1948, Perth, WA, Australia, 1995. (https://10.1109/ICNN.1995.488968)

[6] W. J. Ryu, G. B. Satrya, and S. Y. Shin, "Bio-Inspired scheduling for factory automation in the TD-LTE system," *IETE Tech. Rev.*, vol. 39, no. 5, pp. 1189-1207, 2022. (https://doi.org/10.1080/02564602.2021.1994043)

[7] Z. Li, M. A. Uusitalo, H. Shariatmadari, and B. Singh, "5G URLLC: Design challenges and system concepts," in *Proc. 2018 15th ISWCS*, pp. 1-6, Lisbon, Portugal, 2018. (https://doi.org/10.1109/ISWCS.2018.8491078)

[8] W. J. Ryu and S. Y. Shin, "Performance evaluation of a power allocation algorithm based on dynamic blocklength estimation for URLLC in the multicarrier downlink NOMA systems," *Turkish J. Electr. Eng. and Comput. Sci.*, vol. 29, no. 1, 2021. (https://doi.org/10.3906/elk-2004-137)

[9] T. Kim and I. Bang, "A study on multi-preamble based random access for 5G URLLC: Cross-layer approach," *J. KICS*, vol. 46, no. 2, pp. 238-245, Feb. 2021. (https://doi.org/10.7840/kics.2021.46.2.238)

[10] W. J. Ryu, J.-W. Kim, S.-Y. Shin, and D.-S. Kim, "On the performance evaluations of cooperative retransmission scheme for cell-edge users of URLLC in multi-carrier downlink NOMA systems," *Sensors*, vol. 21, no. 21, 2021. (https://doi.org/10.3390/s21217052)

[11] S. Bhardwaj, R. R. Ginanjar, and D. S. Kim, "Deep Q learning based resource allocation in industrial wireless networks for URLLC," *IET Commun.*, vol. 14, no. 6, 2020. (https://doi.org/10.1049/iet-com.2019.1211)

[12] A. A, Mirani, G. V. Hernandez, A. Awasthi, and J. Walsh, "Key challenges and emerging technologies in industrial IoT architectures: A review," *Sensors*, vol. 22, no. 15, Aug. 2022. (https://doi.org/10.3390/s22155836)

[13] B. S. Khan, S. Jangsher, A. Ahmed, and A. Al-Dweik, "URLLC and eMBB in 5G industrial IoT: A survey," *IEEE Open J. Commun. Soc.*, vol. 3, pp. 1134-1163, 2022. (https://doi.org/10.1109/OJCOMS.2022.3189013)

[14] J. Ding, M. Nemati, S. R. Pokhrel, O.-S. Park, J. Choi, and F. Adachi, "Enabling grant-free URLLC: An overview of principle and enhancements by massive MIMO," *IEEE Internet of Things J.*, vol. 9, no. 1, pp. 384-400, Jan. 2022. (https://doi.org/ 10.1109/JIOT.2021.3107242)

[15] S. Saha, V. B. Sukumaran, and C. R. Murthy, "On the minimum average age of Information in IRSA for Grant-Free mMTC," *IEEE J. Sel. Areas in Commun.*, vol. 39, no. 5, pp. 1441-1455, May 2021. (https://doi.org/10.1109/JSAC.2021.3065065)

[16] I. Ayoub, I. Hmedoush, C. Adjih, K. Khawam, and S. Lahoud, "Deep-IRSA: A deep reinforcement learning approach to irregular repetition slotted ALOHA," in *Proc. 2021 10th IFIP Int. Conf. (PEMWN)*, pp. 1-6, Ottawa, ON, Canada, 2021. (https://doi.org/10.23919/PEMWN53042.2021.9664720)

[17] J. Sun, R. Liu, Y. Wang, and C. W. Chen, "Irregular repetition alotted ALOHA with priority (P-IRSA)," in *Proc. 2016 IEEE 83rd VTC Spring*, pp. 1-5, Nanjing, China, 2016. (https://doi.org/10.1109/VTCSpring.2016.7504302)

[18] X. Shao, Z. Sun, M. Yang, S. Gu, and Q. Guo, "NOMA-Based irregular repetition slotted ALOHA for satellite networks," *IEEE Commun. Lett.*, vol. 23, no. 4, pp. 624-627, Apr. 2019. (https://doi.org/10.1109/LCOMM.2019.2900319)

[19] I. N. A. Ramatryana, G. B. Satrya, and S. Y. Shin, "Adaptive traffic load in IRSA-NOMA prioritizing emergency devices for 6G enabled massive IoT," *IEEE Wireless Commun. Lett.*, vol. 10, no. 12, pp. 2713-2717, Dec. 2021. (https://doi.org/10.1109/LWC.2021.3113048)

[20] C. Namislo, "Analysis of mobile radio slotted ALOHA networks," *IEEE J. Sel. Areas in Commun.*, vol. 2, no. 4, pp. 583-588, Jul. 1984. (https://doi.org/10.1109/JSAC.1984.1146088)

[21] N. Abramson, "The ALOHA system: Another

alternative for computer communications," in *Proc. Fall Joint Computer Conf.*, Nov. 1970. (https://doi.org/10.1145/1478462.1478502)

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