Wireless Sensor Networks & IoT Devices Course Assignment

Comparative Study of Pure ALOHA vs. Slotted ALOHA Protocols using MATLAB

CCEN 481

Shayma Mohammed Alteneiji | 100063072

Wahaj Ahmed | 100063485

Course Instructor: Prof. Arafat Al-dweik

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I. Pure ALOHA Protocol Theory

The pure ALOHA protocol is simple but elegant. The idea of the protocol is that each station transmits a frame whenever they have one. The protocol details are shown in the flowchart given in Figure 1. The flow chart describes the process as follows:

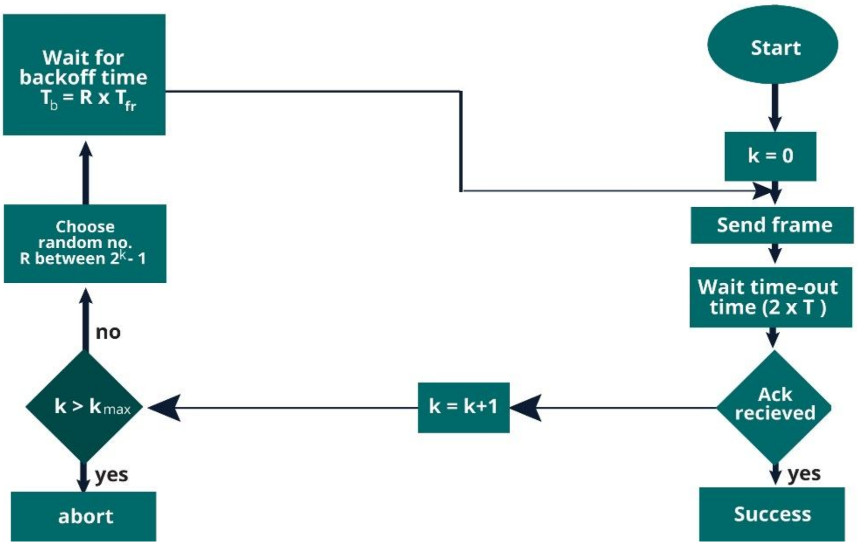

Figure 1. Pure ALOHA protocol flow chart [1].

(1) a station generates a frame and transmits it.

(2) the station waits for a time-out period equal to $2 \times T_p$, where T_p is the propagation delay between the two most distant stations.

(3) if the station receives no acknowledgment message during this period, it assumes that a collision has occurred and increments k by one, where k is the number of retransmission attempts.

(4) When the number of retransmission attempts is reached, the station aborts the operation.

(5) otherwise, it would wait for a back-off period. The equation for the back-off period differs for different applications. The most common one is the binary exponential back-off period (BEB). In the binary exponential period, the station waits for a period equal to $R \times T_f$, T_f is the frame transmission time and R is a random number between 0 and $2^K - 1$, such that the average waiting time doubles for every retransmission attempt.

I. I What Guarantees a Successful Transmission?

A station's packet reaches its destination successfully if, during transmission, it does not overlap with any packet from another station. This condition is satisfied if no station transmits during the time window from $t - T_f$ to $t + T_f$. The duration of this window is equal to $2 \times T_f$, and it is defined as the vulnerable time, the period during which a packet is susceptible to collisions from packets transmitted by other stations. In the next section, we examine the probability of successful transmissions by introducing the concept of a network's offered load and exploring its relationship with the vulnerable time.

I. II Network Offered Load

A network's offered load is the average number of packets generated by the system during one time slot or one frame transmission time. Specifically, this is the definition of normalized offered load, which is given in units of packets generated per one time slot. The equation for the offered load (given by G) is shown below.

$$G = \lambda \times T_f + N_{queuing} \times q$$

A network's offered load is controlled by lambda λ - a Poisson distribution parameter which describes the average packet arrival rate, the frame transmission time T_f, the number of stations waiting for retransmission $N_{queuing}$ (hence, G is controlled by the number of maximum retransmission attempts), and finally the probability of retransmission q.

Considering firstly the simple case when retransmissions are not allowed (collided packets are lost), G then simplifies to the first term only. Since packet arrival within a given time slot follows a Poisson distribution, the time difference between consecutive packets, or the inter-arrival time (τ), follows an exponential distribution.

The exponential distribution is characterized by the parameter λ, which is the reciprocal of the mean. The mean describes the average time between each consecutive packets. Figure 2 shows the exponential distribution PDF when λ = 500 and λ = 1000 packets per unit time. The curve becomes steeper as λ increases, resulting in the greater likelihood of shorter inter-arrival times (τ). Therefore, increasing λ result in packets arriving more frequently and increases the probability of overlap between transmitted packets, consequently leading to greater probability of packet collisions.

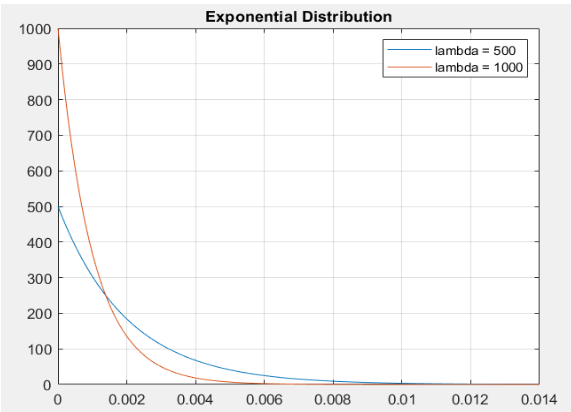

Figure 2. Exponential distribution probability density function when $\lambda = 500$*, and* $\lambda = 1000$

Maximizing a network's efficiency (throughput) is therefore closely tied to its offered load and hence the selected λ. Moreover, λ can be expressed as $p \times N$, where N is the number of users in a given network and p is the probability of transmission of each user. This allows for a better understanding of the meaning of λ in a given scenario and how to control it.

Intuitively, given pure ALOHA's vulnerable time window $(2 \times T_f)$, we can arrive to the conclusion that throughput is maximized when G = ½. This is because, if on average, stations transmit only one frame during two time slots, then collisions are avoided while the time resource is used efficiently. When G is lower than ½, collisions decrease; however, the channel remains idle for long periods, resulting in lower throughput. On the other hand, offered loads higher than ½ result in increased collisions. In the next section, we mathematically derive the throughput equation and prove the value of G at which throughput is maximized for pure ALOHA.

I. III Derivation of Pure ALOHA Throughput Equation

As stated above, packet arrivals in each time slot follow the Poisson distribution. Let k be a random variable representing the number of transmitted packets per time slot. The probability that k packets arrive within two consecutive time slots is given as shown below. (Note that G is substituted for λ in the Poisson distribution, where λ, in units of packets per one time slot or frame transmission time, is equal to G.)

$$P(k) = \frac{2G^k e^{-2G}}{k!}$$

The probability of a successful transmission occurs when k = 1, meaning only one packet arrives within two time slots:

$$P(success) = P(k = 1) = 2Ge^{-2G}$$

Therefore, throughput, which is the fraction of successful transmissions over the transmission time slots, is given as follows:

$$Throughput = \frac{Successful\ Transmissions}{Total\ Time\ Slots} = \frac{2Ge^{-2G}}{2} = Ge^{-2G}$$

The value of G corresponding to maximum throughput can be determined by finding the derivative of throughput with respect to time and equating it to zero, as shown below. Maximum throughput occurs when G = ½, as previously speculated from the vulnerable time, and maximum theoretical throughput for pure ALOHA is $\frac{1}{2e} \approx 0.184$. This means that for every 5000 packets transmitted, only 92 survive.

$$\frac{\partial}{\partial G} Ge^{-2G} = e^{-2G} - 2Ge^{-2G} = 0 \rightarrow G_{max} = \frac{1}{2}$$

I. IV Effects of Retransmissions

In the previous sections, we only considered the network's offered load contributed by stations transmitting original packets. As the offered load equation shows (given in Section I. II), retransmissions result in the offered load being greater than the intended value. Retransmitting stations increase the channel's congestion, resulting in instability and an aggressive drop in throughput, potentially leading to starvation. The known throughput plot compresses and shifts to the left as the number of allowed retransmission attempts increases. The drop in throughput as the load increases can be made more gradual by decreasing the probability (q) of retransmission. This effect is studied in the protocol simulation.

II. Slotted ALOHA Protocol Theory

The theory of slotted ALOHA is similar to Pure ALOHA with the key difference that stations are now forced to transmit only at the begging of synchronized time slots. The duration of the time slots is equal to the frame transmission time. The reduction in the randomness of transmission helps avoid collisions and improves the network's throughput.

For slotted ALOHA, the vulnerable time is reduced to T_f. If only one station transmits during a time slot, the generated frame will reach its destination successfully. In the same way we intuitively found the offered load G at which throughput is maximized for pure ALOHA, we can infer that for slotted ALOHA, maximum throughput occurs when $G = 1$. The throughput equation can be derived as follows. The probability that k number of packets arrive within *one* time slots is given as shown below:

$$P(k) = \frac{G^k e^{-G}}{k!}$$

The probability of a successful transmission occurs when $k = 1$, meaning only when one packet arrives within a time slot. The throughput, can therefore, be calculated as:

$$Throughput = \frac{Successful\ Transmissions}{Total\ Time\ Slots} = P(success) = P(k=1) = Ge^{-G}$$

Mathematically, it is proven that maximum throughput occurs when $G = 1$, as shown below. The maximum theoretical throughput for slotted ALOHA is $\frac{1}{e} \approx 0.368$. This means that for every 5000 frames transmitted, only 184 packets survive.

$$\frac{\partial}{\partial G} Ge^{-G} = e^{-G} - Ge^{-G} = 0 \rightarrow G_{max} = 1$$

The retransmission effects also occur in slotted ALOHA. As retransmission attempts increase, throughput degrades rapidly, the effect is also studied in simulation. In the next section, the simulation assumptions, parameters, and flowcharts are discussed.

III. Protocol Simulation

Both pure and slotted ALOHA were simulated in MATLAB. Random packet inter- arrival times were generated for N users using an exponential distribution, hence the total number of packets arriving within a given time frame follow the poison distribution. Collision detection was implemented as well as retransmissions. A binary exponential backoff was also used to generate the random waiting time before attempting retransmission. Finally, the throughput was calculated and was plotted against the offered load. The next section discusses the assumptions made and the simulation parameters set.

III. I Assumptions and Parameters

The following assumption and parameters are used in the simulations:

Assumptions:

- Packet arrivals follow a Poisson distribution and backoffs follow BEB
- Frame transmission times and propagation times are constant for all packets regardless of user
- If two packets slightly overlap in their respective transmission durations, the entire packet is lost
- Users have synchronized clocks (for slotted)
- No processing time taken for calculating new transmission times
- Need 1 packet per 2 slots for successful transmission (Pure ALOHA)
- Need 1 packet per 1 slot for successful transmission (Slotted ALOHA)

Parameters:

- Average packet arrival rate (packets per second)
- Max retransmissions (maximum number of retransmissions attempts before aborting)
- Number of users
- Frame transmission time
- Max propagation delay
- Simulation duration

III. II Pure ALOHA and Slotted ALOHA Code Flowchart

The code flowcharts are given below in figures 3, 4 and 5.

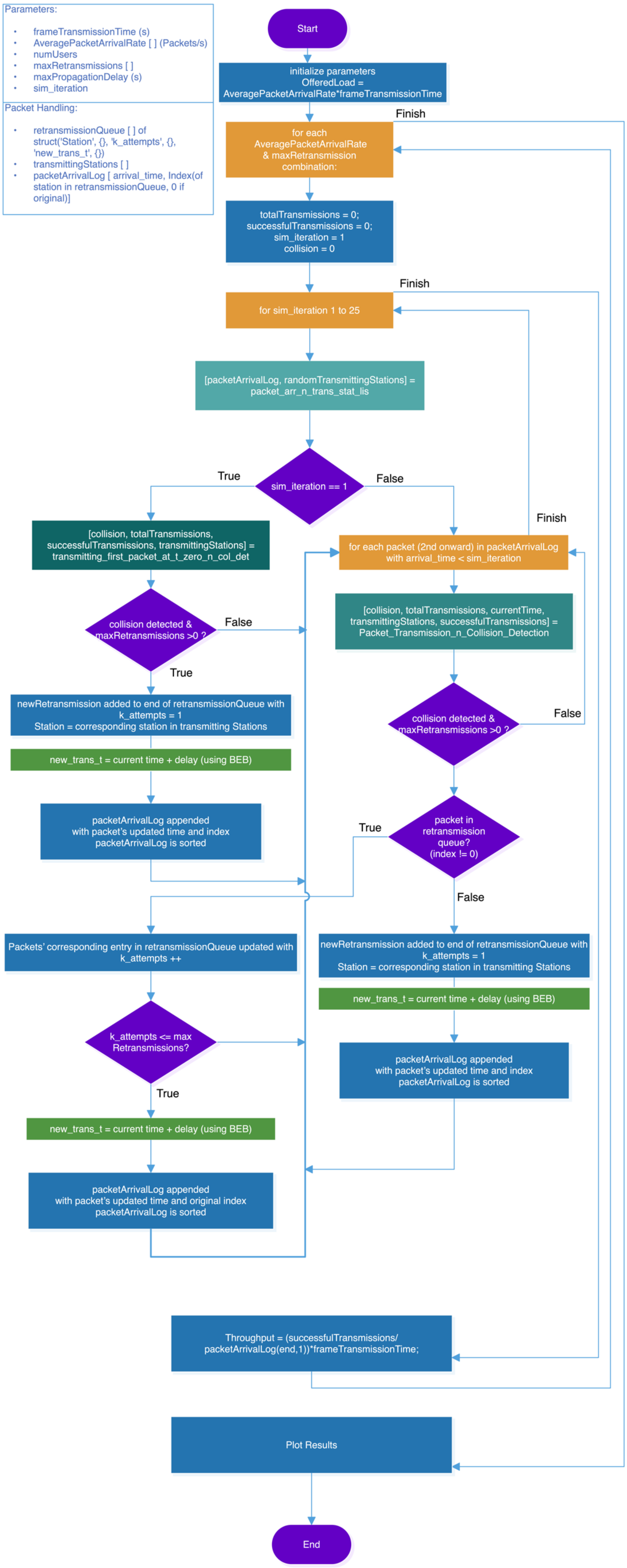

Figure 3. Pure ALOHA main code flowchart

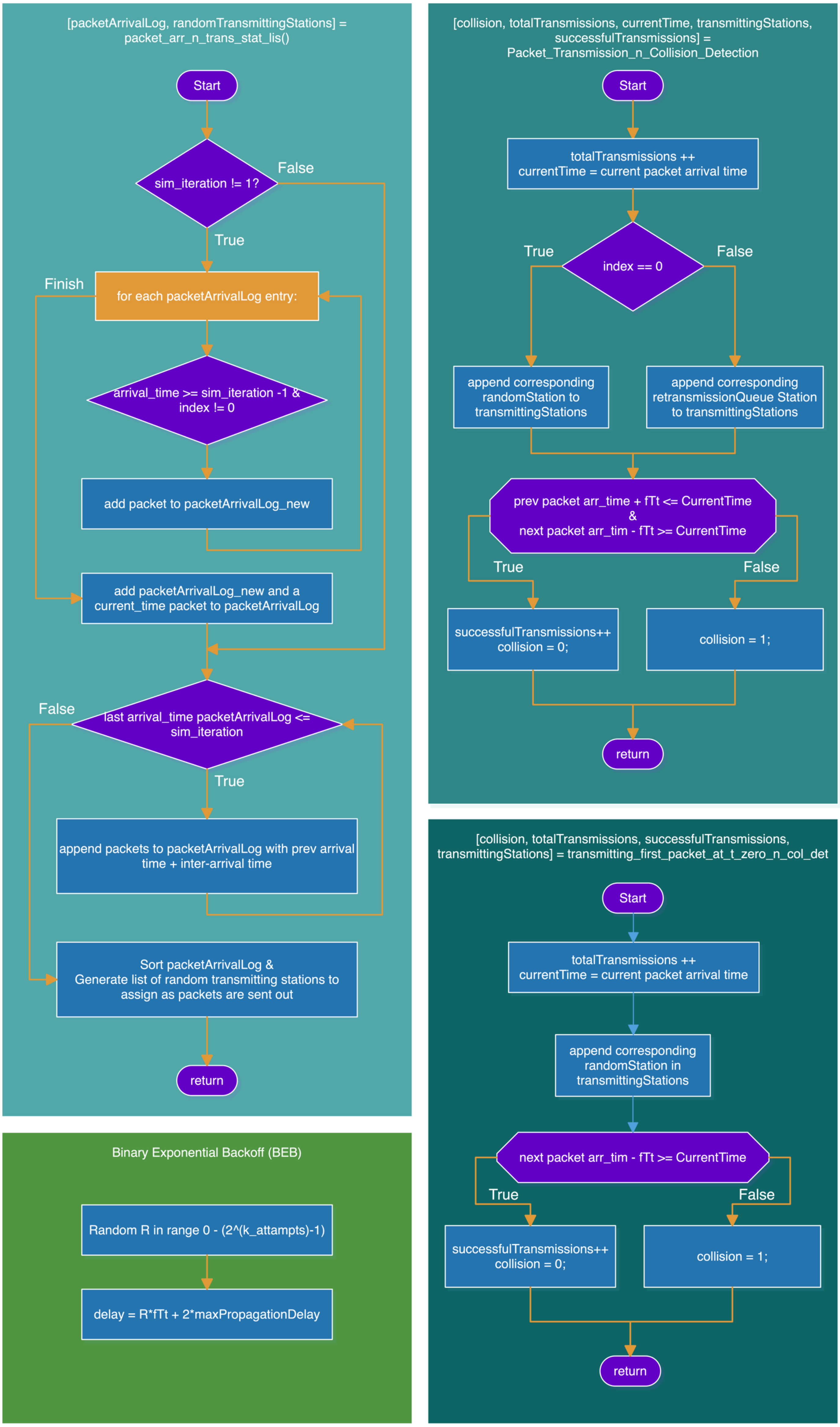

Figure 4. Pure ALOHA code functions

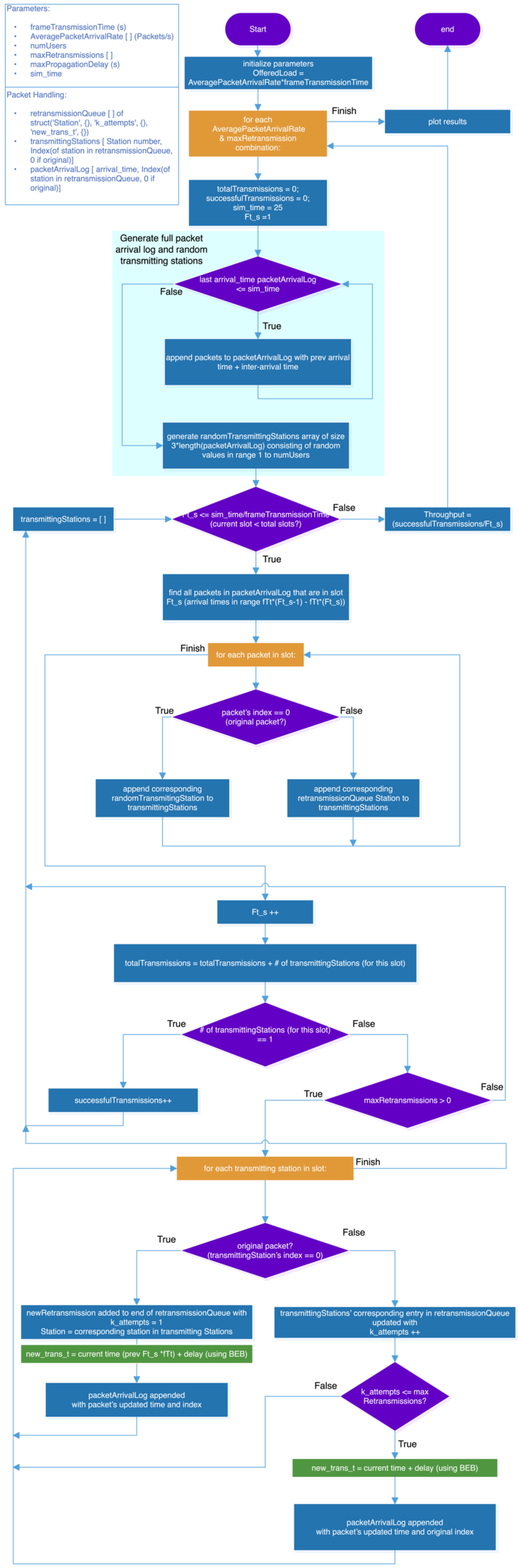

Figure 5. Slotted ALOHA code flowchart

VI. Simulation Results and Analysis

The simulation codes and results are given in the GitHub respiratory linked here: https://github.com/Shayma0123/CCEN481-Assignment.

Figure 6 shows the resulting throughput versus offered load plot for Pure ALOHA with various maximum retransmission attempts. The plot follows the expected behaviour; when no retransmissions are allowed, the resulting plot closely following the theoretical throughout equation, with the peak throughput of approximately 18.4 % occurring at G = ½, as expected.

As mentioned earlier, instead of expressing G as a function of lambda and the frame transmission time, it can be expressed as a function N, and p as shown below. By varying the load (G) from 0.1 to 3, we effectively increase the transmission probability of each user or station, assuming the number of stations remains constant or vice versa. For loads lower than ½, (representing small- sized networks or transmission), the likelihood of collisions decreases. However, the network is under utilizing its time resources, leading to lower throughput.

$$G = N_{users} \times p + N_{queuing} \times q$$

As the load increases beyond ½, (representing large-sized networks or high transmission probability), the likelihood of collisions increases significantly, resulting in a rapid decline in throughput with higher loads.

As retransmission attempts increase, retransmitting stations contribute further to channel congestion for higher loads, causing the throughput to degrade significantly. The plots for various retransmission attempts follow the description given above, where the plots compress and shift further to the left with increased retransmission attempts. In the simulation, retransmitting stations retransmit with a probability (q) of 1. In section V, we discuss the effect of varying the retransmission probability (q).

Figure 7 shows the simulation results for Slotted ALOHA. The same trend observed in pure ALOHA is present and the simulation results capture the expected behaviour. When comparing the two MAC protocols, it is clear that Slotted ALOHA has greater efficiency, as it sustains higher throughput under heavier loads. The peak throughput for Slotted ALOHA is 36.8 %, occurring when G = 1. This improvement is due to the reduction in the vulnerable time and decreased randomness, resulting in a 100% increase in efficiency compared to the original pure ALOHA protocol.

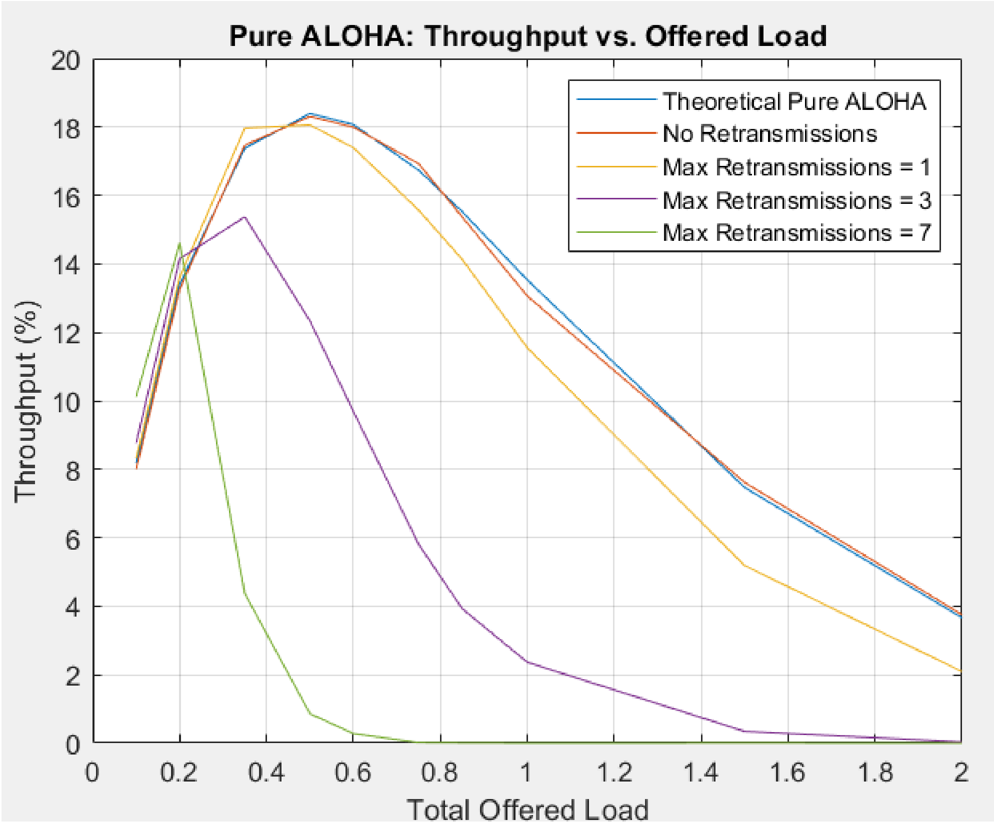

Figure 6. Pure ALOHA Throughput Plot Simulation Results.

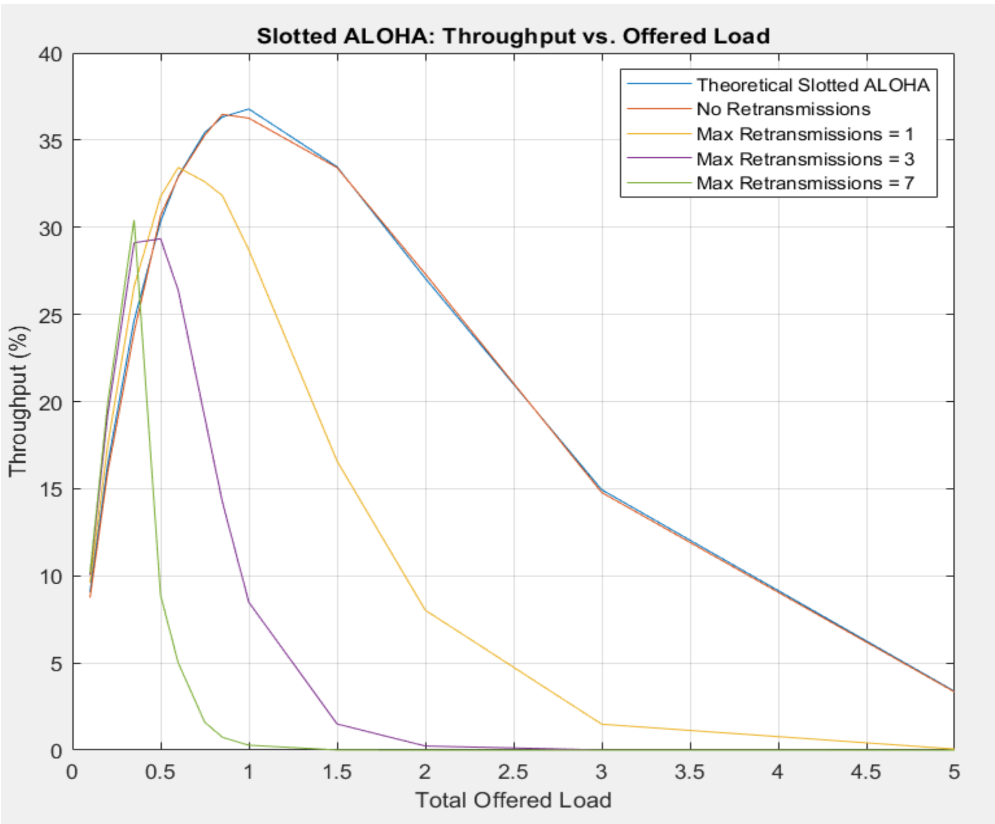

Figure 7. Slotted ALOHA Throughput Plot Simulation Results.

Figure 8 shows the Slotted ALOHA's theoretical plot superimposed on the Pure ALOHA plot for clearer comparison. Slotted ALOHA outperforms Pure ALOHA across the different loads (high and low). Therefore, for a reasonable throughput performance, Pure ALOHA is only suitable for small-sized networks (lower users and lower offered loads).

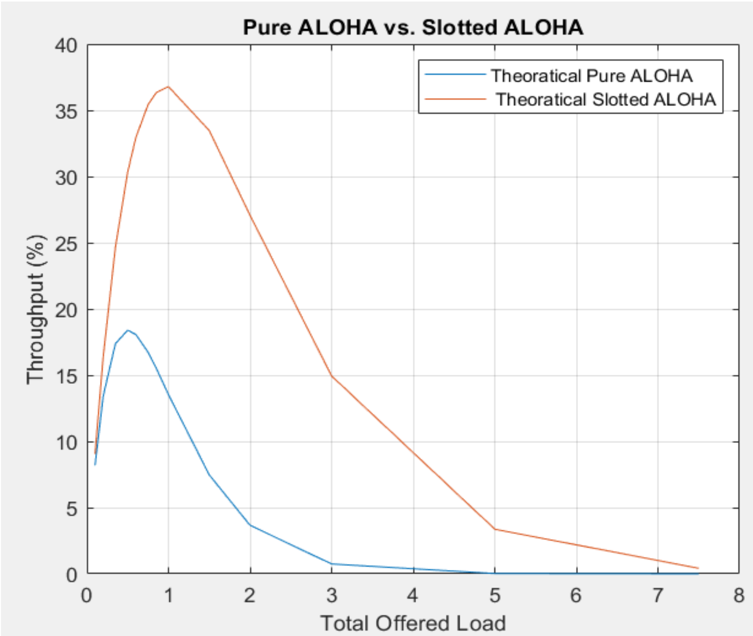

Figure 8. Pure ALOHA versus Slotted ALOHA Throughput Plots.

As slotted ALOHA supports heavier loads with reasonable throughputs, it is more suitable for large-sized networks. However, this introduces greater cost requirements due to the need of synchronizing the stations to the same time clock (to ensure stations transmit only at the begging of each time slots). Hence, in scenarios where cost is less crucial than network throughput performance, Slotted ALOHA protocol should be selected as the MAC protocol, on the other hand, when delays are tolerable (due to reduced throughput) and costs are constrained, Pure ALOHA protocol should suffice.

Moreover, the MATLAB simulation of both protocols printed debugging lines in the Command Window to verify the working of the code and detect logical errors. Snippets of these outputs are provided in Appendix A. In the next section, we discuss the effects of varying the retransmission probability.

V. Effect of Varying the Retransmission Probability

The previous section discussed the simulation results when retransmitted stations were allowed to retransmit with probability 1. This resulted in a rapid and significant decline in throughput as the maximum number of retransmission attempts increased. The effect is seen in Figures 6, and 7. Particularly, a greater decline was observed for Slotted ALOHA.

To study the impact of varying the retransmission probability, we simulated both MAC protocols using a retransmission probability equal to q. The retransmission decision (yes—retransmit, or no—do not retransmit) was generated using a Bernoulli distribution. The probability q was sent to be the reciprocal of the number of stations queued for retransmission. Hence q is dynamic, as the number of queuing stations increases, the retransmission probability decreases. This helps stabilize both channel congestion and network throughput. A more detailed flowchart of the code is illustrated in figure 9.

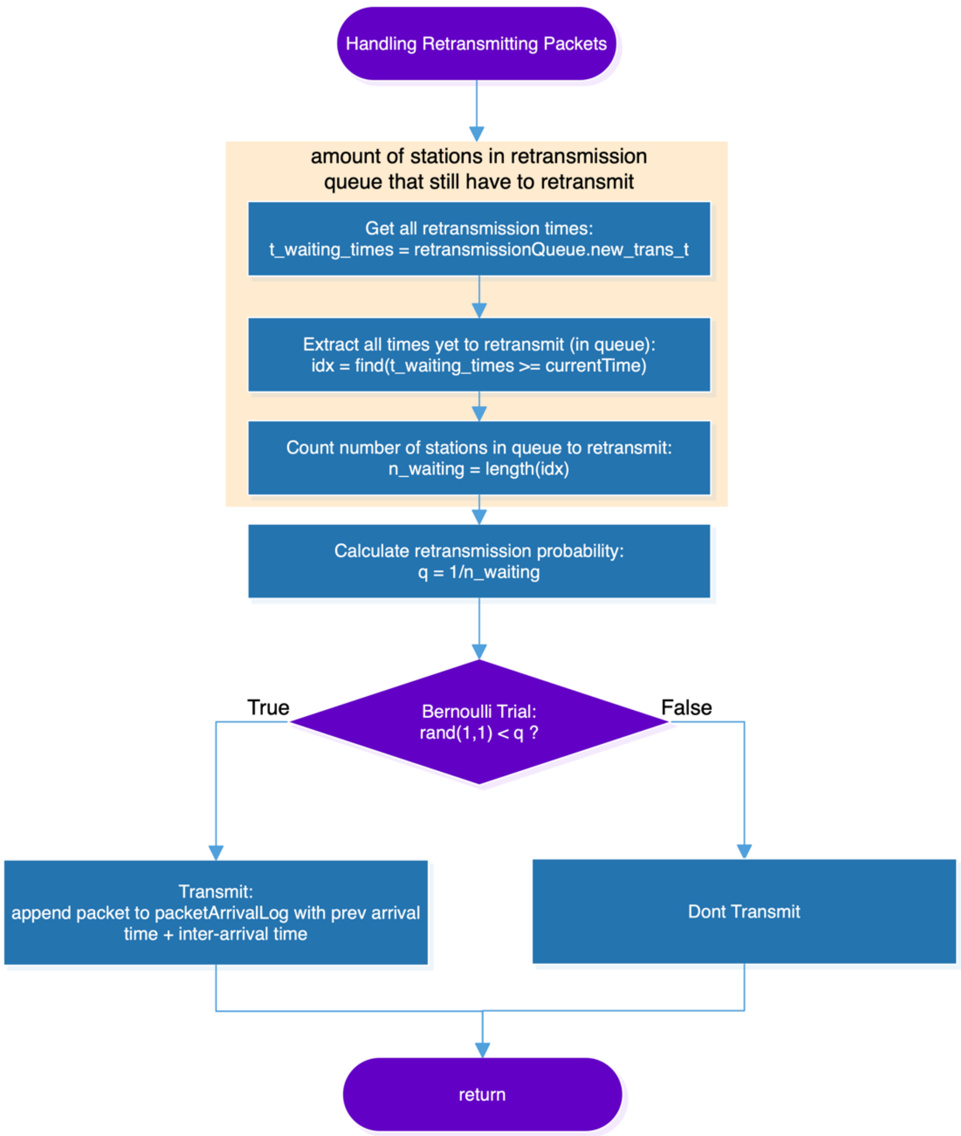

Figure 9. handling packet retransmissions with dynamic probability of retransmission code flowchart

Figure 10 presents the throughput results for Pure ALOHA, comparing the two cases: when the retransmission probability is fixed and set to 1 and when it is set to the variable probability q. The number of maximum retransmission attempts was set to 3. The results demonstrate that reducing the retransmission probability significantly improves throughput efficiency. However, this improvement comes at the cost of a higher number of permanently lost (i.e., non-retransmitted) collided packets. Figure 11 shows the simulation results for Slotted ALOHA. Throughput is significantly improved, and its performance edge remains evident even under the varying retransmission probability.

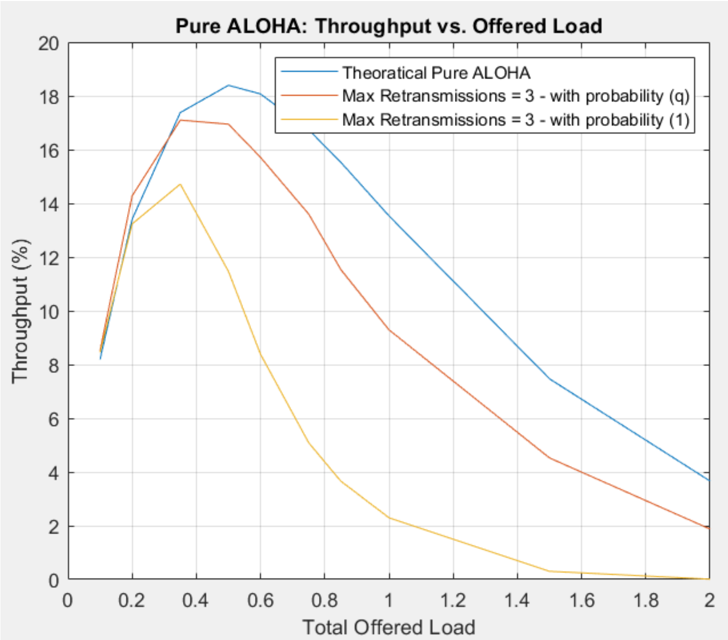

Figure 10. Pure ALOHA Throughput Simulation Results Under Varying Retransmission Probabilities.

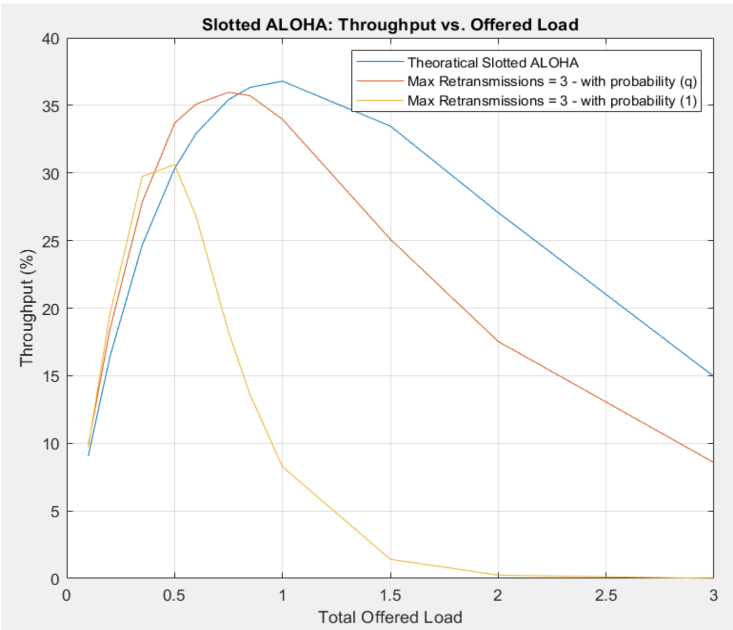

Figure 11. Slotted ALOHA Throughput Simulation Results Under Varying Retransmission Probabilities.

VI. Conclusion

In this assignment, we explored Pure and Slotted ALOHA, two MAC protocols widely used for wireless communication. They differ in that Pure ALOHA allows sending packets as soon as they are generated, while Slotted ALOHA only allows transmissions at the beginning of a synchronized time slot.

First, we calculated the theoretical throughput of both protocols based on a Poisson packet arrival distribution. The maximum throughputs were 0.184 at G= ½ for Pure ALOHA and 0.368 at G=1 for Slotted ALOHA.

Next, we simulated both protocols on MATLAB and plotted throughput vs offered load curves for varying amounts of retransmissions allowed. We also compared them with the theoretical throughput curves.

All the resulting graphs followed the expected trend: throughput initially increased with offered load, reached a peak, and then declined. This behaviour reflected the network's transition from underutilization (low offered load and minimal collisions) to overutilization (high offered load with frequent collisions).

Both simulations for pure and slotted ALOHA without retransmissions were closely matched to their respective theoretical curves, with slotted ALOHA having double the maximum throughput of Pure ALOHA. However, as we increased the number of retransmissions, a lower maximum throughput was reached at a lower offered load. The curve then fell sharply after the peak throughput, showing quick degradation in performance. This is because as the offered load increased, collisions increased, leading to more retransmissions which then led to even more collisions.

Finally, we explored retransmissions with a probability inverse to that of the number of stations waiting to retransmit. This gave a much better performance when compared to always sending the retransmitting packet as we did earlier.

In conclusion, this assignment taught us how packet arrival rates, retransmission strategies and other parameters affect network performance. Simulating and analysing both ALOHA protocols gave us valuable insights into the trade-offs between the simplicity of Pure ALOHA, but with low throughput and the synchronization overhead required by Slotted ALOHA but with the benefit of double the throughput. These features give each protocol distinct real-world applications.

Pure ALOHA is better applicable for smaller, simpler networks where cost and complexity are concerns, but lower throughput is acceptable. On the other hand, Slotted ALOHA, with its higher throughput, is ideal for larger networks where performance is prioritized over the additional synchronization overhead.

Pure ALOHA is known to be used in older satellite communications and early wireless networks, although it may still be used today for small scale radio communication. On the other hand, slotted ALOHA is used in GSM cellular networks, Wi-Fi networks and in IoT devices.

To further understand and explore the ALOHA protocols, it may be worth investigating the average delay and collision probability for both Pure and Slotted ALOHA as well as other ways to stabilize the network when dealing with high retransmission rates.

VII. References

[1]. R. Kar, "Aloha: A random access method of multiple access in Computer Network," *Includehelp.com*, 2023. https://www.includehelp.com/computer-networks/aloha-a-random-access-method-of-multiple-access.aspx (accessed Apr. 05, 2025).

[2]. B. A. Forouzan and Sophia Chung Fegan, *Data communications and networking*. Boston: Mcgraw-Hill Higher Education, C, 2007.

[3]. E. Modiano, "Lecture 10/11: Packet Multiple Access: The Aloha protocol." Accessed: Apr. 05, 2025. [Online]. Available: https://web.mit.edu/modiano/www/6.263/lec10.pdf

VIII. Appendix A

VIII. I Appendix A – Pure ALOHA Debugging Lines (Max Retransmission = 1)

```
Station 652 transmitted successfully
Station 771 transmits a new packet at t = 0.0128495
Station 771's packet collided with another packet. The station waits for retransmission
Station 771 will re-transmits at t = 0.0129
Station 771 is re-transmiting at t =0.0128695
Station's 771 packet collides with anther packet. The station waits for re-transmission
Maximum number of attempts is reached for station 771
Station 137 transmits a new packet at t = 0.0132486
Station 137's packet collided with another packet. The station waits for retransmission
Station 137 will re-transmits at t = 0.0133
Station 137 is re-transmiting at t =0.0132686
Station's 137 packet collides with anther packet. The station waits for re-transmission
Maximum number of attempts is reached for station 137
Station 937 transmits a new packet at t = 0.0143577
Station 937 transmitted successfully
Station 51 transmits a new packet at t = 0.0201534
Station 51's packet collided with another packet. The station waits for retransmission
Station 51 will re-transmits at t = 0.0212
Station 352 transmits a new packet at t = 0.0209201
Station 352's packet collided with another packet. The station waits for retransmission
Station 352 will re-transmits at t = 0.0209
Station 352 is re-transmiting at t =0.0209401
Station's 352 packet collides with anther packet. The station waits for re-transmission
Maximum number of attempts is reached for station 352
Station 51 is re-transmiting at t =0.0211734
Station's 51 packet collides with anther packet. The station waits for re-transmission
Maximum number of attempts is reached for station 51
Station 802 transmits a new packet at t = 0.0218011
Station 802's packet collided with another packet. The station waits for retransmission
Station 802 will re-transmits at t = 0.0228
Station 802 is re-transmiting at t =0.0228211
```

VIII. II Appendix A – Slotted ALOHA Debugging Lines (Max Retransmission = 1)

```
Station 1006 is transmitting an original packet during the 1-th slot
Station 1006 transmits successfully
Station 52 is transmitting an original packet during the 2-th slot
Station 964 is transmitting an original packet during the 2-th slot
Station 1183 is transmitting an original packet during the 2-th slot
Station's 52 packet collides with anther packet. The station waits for re-transmission
Station's 52 will re-transmits at t = 0.0032000
Station's 964 packet collides with anther packet. The station waits for re-transmission
Station's 964 will re-transmits at t = 0.0022000
Station's 1183 packet collides with anther packet. The station waits for re-transmission
Station's 1183 will re-transmits at t = 0.0032000
Station 964 is re-transmitting a packet during the 3-th slot
Station 964 transmits successfully
Station 91 is transmitting an original packet during the 4-th slot
Station 52 is re-transmitting a packet during the 4-th slot
Station 1183 is re-transmitting a packet during the 4-th slot
Station's 91 packet collides with anther packet. The station waits for re-transmission
Station's 91 will re-transmits at t = 0.0042000
Maximum number of attempts is reached for station 52
Maximum number of attempts is reached for station 1183
Station 745 is transmitting an original packet during the 5-th slot
Station 91 is re-transmitting a packet during the 5-th slot
Station's 745 packet collides with anther packet. The station waits for re-transmission
Station's 745 will re-transmits at t = 0.0062000
Maximum number of attempts is reached for station 91
```