Low Reliable and Low Latency Communications for Mission Critical Distributed Industrial Internet of Things

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Keywords and some definitions

Reliablity

Reliability is defined as the probability that a product, system, or service will perform its intended function adequately for a specified period of time, or will operate in a defined environment without failure.

Latency

Latency from a general point of view is a time delay between the cause and the effect of some physical change in the system being observed.

Internet of things(LoT)

The Internet of things describes the network of physical objects/”things”—that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet.

Consensus

Consensus decision-making is group decision-making processes in which participants develop and decide on proposals with the aim, or requirement, of acceptance by all.

Q-function

In statistics, the Q-function is the tail distribution function of the standard normal distribution. In other words, Q(x) is the probability that a normal (Gaussian) random variable will obtain a value larger than x standard deviations.

$$Q(x) = P(X > x) \tag{1}$$

where,

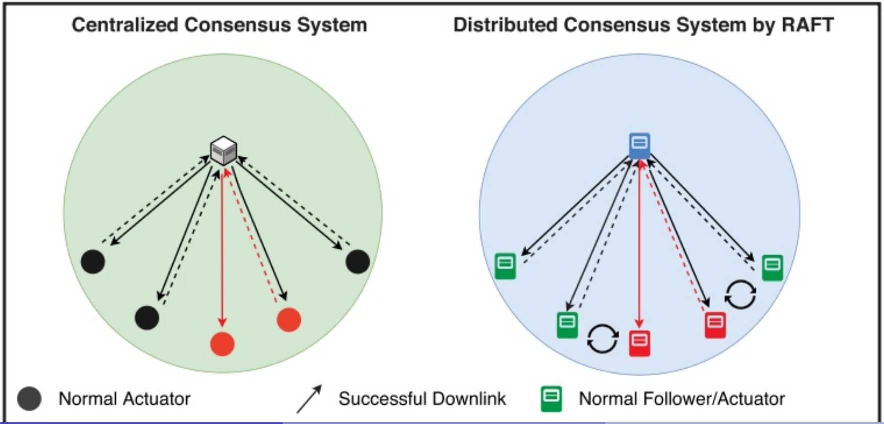
$$x = \frac{x - \mu}{\sigma}$$

It is a decreasing monotonous function.

Centralised v/s Distributed consensus system

Motive:

In some critical IIoT application scenarios, URLLC needs to provide an end-to-end latency lower than 1 ms and exceedingly high reliability more than $1 - 10^9$



Raft

There are three roles in Raft algorithm.

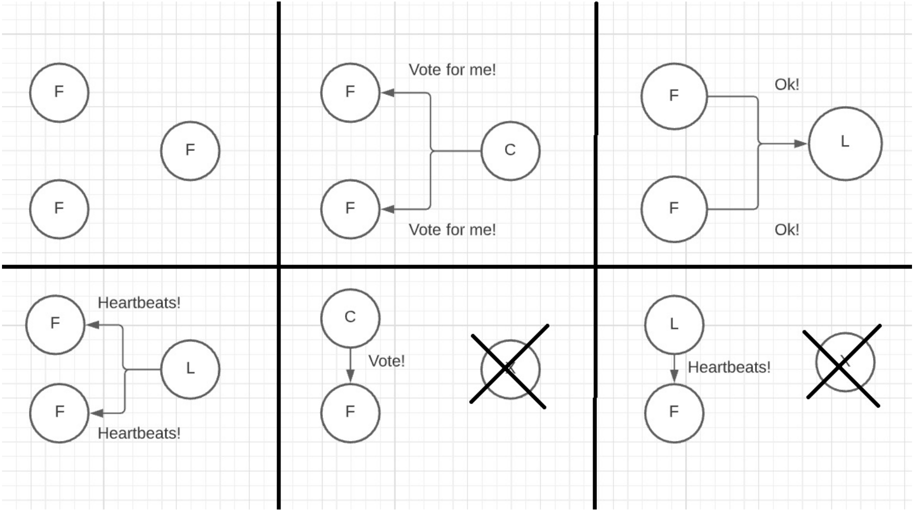


Figure: Election of a leader

Log Replication

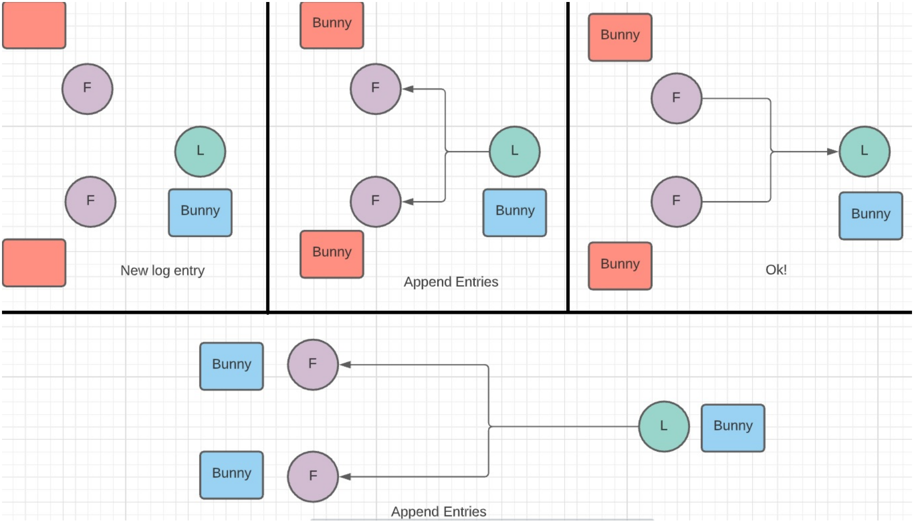


Figure: Log Replication

Reliability of Communication System With Raft

1. Let us consider N nodes in a distributed system with Raft CM
2. A reliable critical decision requires that over $\frac{N-1}{2}$ followers who can receive log entries from the leader and send the confirmed messages back to the leader to achieve the commitment of log replication.
3. It is worth to mention that 50% is the fault tolerance of Raft.

Reliability of Communication System With Raft

Consensus success rate

Let P_l be communication link success rate and P_C be consensus success rate of the system.

$$P_C = \sum_{i=\frac{N-1}{2}}^{N-1} \binom{i}{N-1} P_l^i (1-P_l)^{N-1-i} \times \sum_{j=\frac{N-1}{2}}^{i} \binom{j}{r} P_l^j (1-P_l)^{i-j} \tag{2}$$

Reliability of Communication System With Raft

1. The first summation represents the probability that the majority of followers can download the log entry from the leader.
2. The second summation equals to the probability that the majority of followers can upload their confirmation back to the leader.
3. The number of successful uplink transmission is never larger than the number of successful downlink transmissions.

Note

According to the (2), to satisfy the most stringent reliability requirement in IIoT, i.e., the consensus failure rate $1 - P_C$ is less than 10^{-9}, the nodes number N should not be less than 69, 31, 12, 5, when the link success rate P_l is 90%, 95%, 99% and 99.9%, respectively.

Reliability Gain

Reliability Gain

Reliability Gain is a parameter (also can be interpreted as reliability amplification factor) to represent the quantitative relationship between the reliabilities of consensus and communication link.

$$log(1 - P_C) = klog(1 - P_l) + h \tag{3}$$

where, reliability gain, $k = \frac{N+1}{2}$ and intercept $h = log\left(\binom{\frac{N-3}{2}}{N-1}\right) + \triangle h$

Reliability Gain

1. The consensus failure rate and link failure rate are in linear relation when the nodes number N is constant.
2. With fixed link reliability, the increasing nodes number rises up the consensus reliability, which proves the increasing monotonicity of consensus success rate P_C with the nodes number N.

TABLE I

ESTIMATED Δh

N	Δh	N	Δh	N	Δh
5	0.472	6	0.704	7	0.797
8	1.081	9	1.214	10	1.509
11	1.668	12	1.965	13	2.144
14	2.441	15	2.635	16	2.931
17	3.136	18	3.431	19	3.645

Relationship Between Latency and Reliability

1. Let us consider a wireless communication model, which aims to analyze the packet error probability of the wireless short package transmissions in URLLC, to find out the relationship between consensus success rate P_C and the consensus latency T.
2. We assume it is caused by downlink and uplink transmission delay, i.e., Raft consensus latency T only composes of communication transmission delay to show the communication impacts on the overall consensus latency.
3. The link failure rate can be written as function as T as follows.

$$1 - P_l = f_Q\left(\frac{B\frac{T}{2N}(C - R) + \frac{\log_2(B\frac{T}{2N})}{2}}{(B\frac{T}{2N})^{1/2}\log_2 e}\right) \tag{4}$$

Relationship Between Latency and Reliability

1. B is the available spectrum bandwidth.
2. R and C are the uplink or downlink transmission rate and channel capacity, respectively.

Note

The overall consensus delay, T , each transmission can have $t = \frac{T}{2N}$ transmission internal since there are N transmissions in both uplink and downlink. Therefore, with a constant N, the increasing consensus delay T can provide more time t for each link transmission, which intuitively can reduce the link failure rate $1 - P_l$.

Relationship Between Latency and Reliability

Latency and Reliability

1. By substituting equation(4) into (2) or (3), we can obtain the relationship of reliability $1 - P_C$ with the latency T .
2. The contradiction of consensus reliability $1 - P_C$ and time delay T can be proved in mathematics by calculating the derivative of the variable Q in Q function.

$$\frac{\delta Q}{\delta T} = \frac{\frac{B}{2N}(C - R) - \frac{1}{2T}\log_2(\frac{TB}{2N}) + \frac{1}{T}(\log_e 2)}{2\sqrt{\frac{TB}{2N}}\log_2 e} \tag{5}$$

Relationship Between Latency and Reliability

Latency and Reliability

1. The derivative $\frac{\delta Q}{\delta T}$ is always positive,which means the variable increases monotonically along with T.
2. Based on the decreasing monotonicity of Q-function f_Q along with Q and the increasing monotonicity of P_C along with P_I, the time delay of consensus T and consensus reliability $1 - P_C$ are contradictory.

Relationship Between Latency and Reliability

Conclusion

1. The consensus reliability $1 - P_C$ increases monotonically with the nodes number.
2. However, given fixed consensus delay T , increasing node number will also result in a shorter transmission time t $= \frac{T}{2N}$ for each link.
3. Thus causing a smaller P_l, which may turn out a less reliable consensus according to equation (2) or (3). Thus, it is expected that there is an optimal N to achieve maximum consensus reliability.

Simulation Results

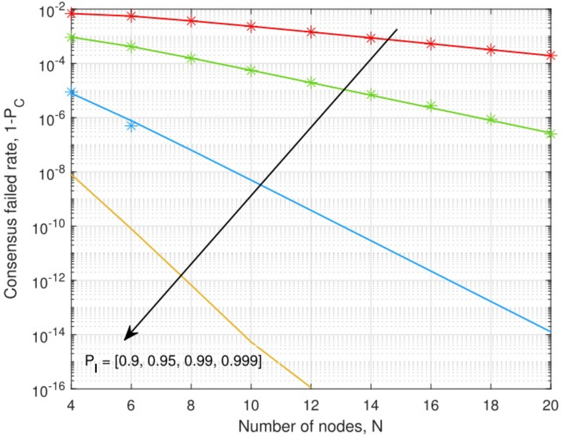


Figure: Consensus failure rate $1 - P_C$ vs. Nodes number N

Simulation Results

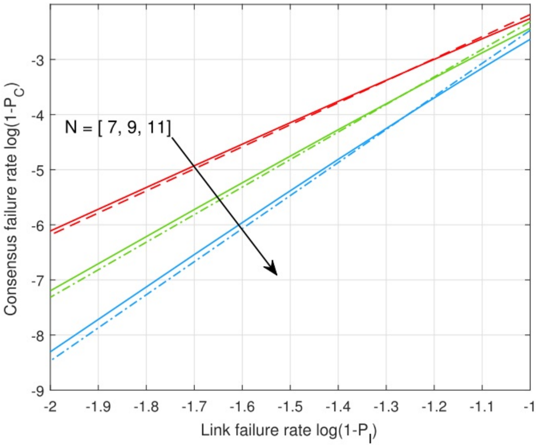


Figure: Consensus failure rate $\log(1 - P_C)$ vs. Link failure rate $\log(1 - P_l)$

Simulation Results

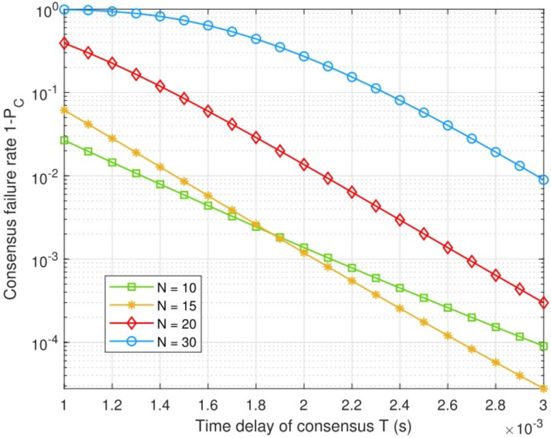


Figure: Consensus failure rate $(1 - P_C)$ vs. Consensus delay T

Simulation Results

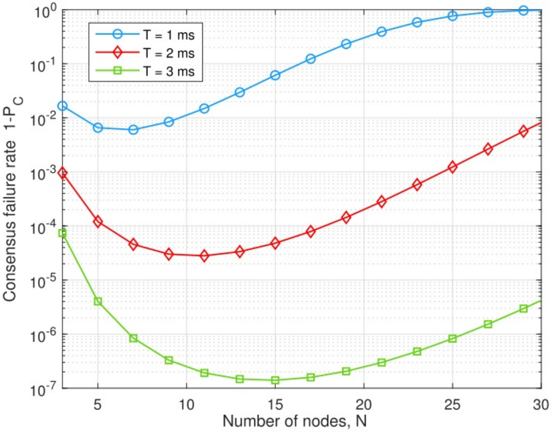


Figure: Consensus failure rate $(1 - P_C)$ vs. Nodes number (N).