Analysis of Energy Consumption Reliability in IoT Network

1 Appendix Mean Time To Failure (MTTF)

The MTTF indicates the mean time a failure can occur or the mean time between failures. In this section, we discuss the results of the MTTF estimator and the Kaplan-Meier (an estimator based on survival curves used as a complement to the MTTF) for Wi-Fi, ESP-NOW, and Bluetooth technologies, both for distances of 8 m and 50 m.

1.0.1 MTTF Wi-Fi Scenarios

Table 1 contains the average of the total experiment time from the four ESP32 present in each scenario and the MTTF resulting from the calculation performed for Wi-Fi technology.

Table 1 MTTF for Wi-Fi Scenarios

Scenarios	Total Experiment Time in Hours	MTTF
Wi-Fi 8 m 5 s BA	02:25	02:21
Wi-Fi 8 m 5 s NB	03:03	02:58
Wi-Fi 8 m 10 s BA	02:53	02:46
Wi-Fi 8 m 10 s NB	03:38	03:29
Wi-Fi 50 m 5 s BA	01:21	01:13
Wi-Fi 50 m 5 s NB	01:52	01:45
Wi-Fi 50 m 10 s BA	01:24	01:12
Wi-Fi 50 m 10 s NB	02:21	02:10

The graph shown in figure 1 shows that the scenarios with Wi-Fi technology do not last long but have long MTTF; that is, the failure in the experiments performed occurs at the end of the battery's charge, showing effective utilization, even with few hours of operation.

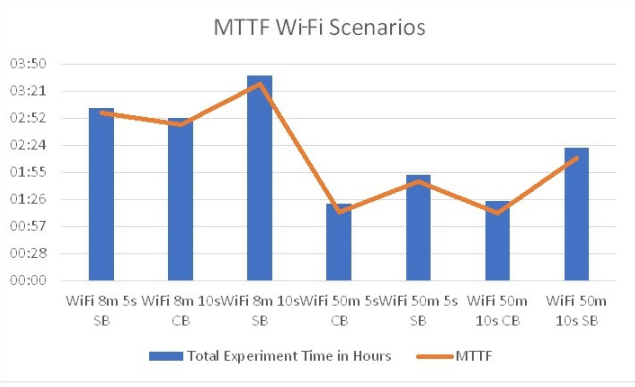

Figure 1: MTTF for Wi-Fi Scenarios

1.0.2 MTTF ESP-NOW Scenarios

Table 2 contains the average of the total experiment time from the four ESP32 present in each of the scenarios and the MTTF resulting from the calculation performed for ESP-NOW technology.

Table 2 MTTF for ESP-NOW Scenarios

Scenarios	Total Experiment Time in Hours	MTTF
ESP-NOW 8 m 5 s BA	11:25	10:47
ESP-NOW 8 m 5 s NB	12:50	12:11
ESP-NOW 8 m 10 s BA	16:18	15:58
ESP-NOW 8 m 10 s NB	16:48	16:30
ESP-NOW 50 m 5 s BA	10:08	09:38
ESP-NOW 50 m 5 s NB	12:10	11:43
ESP-NOW 50 m 10 s BA	14:17	09:54
ESP-NOW 50 m 10 s NB	15:50	08:24

Examining the graph presented in Figure 2, it is possible to notice that almost all ESP-NOW technology scenarios have long MTTF, except for the 50 m 10 s BA and 50 m 10 s NB scenarios. It can be identified that the distance to which the experiment is submitted has a relationship with this lower MTTF, while in the other scenarios, the MTTF happens in the last minutes of the battery, in these two, that happens with an interval of a few hours, being one of 04:23 and the other 07:26.

This result can be analyzed together with the graph presented in Figure **??** (Markov), which shows high oscillation in all the studied states, (FF), (MF), (MM), (LM) and (LL), and with the graph in Figure **??** which illustrates the standard deviation in these scenarios. Even with the failure rate of 2.8 V appearing hours apart from the other scenarios, the two scenarios continue in operation for a while due to the natural recharge of the batteries. Still, it is something to observe if you need stability in the system.

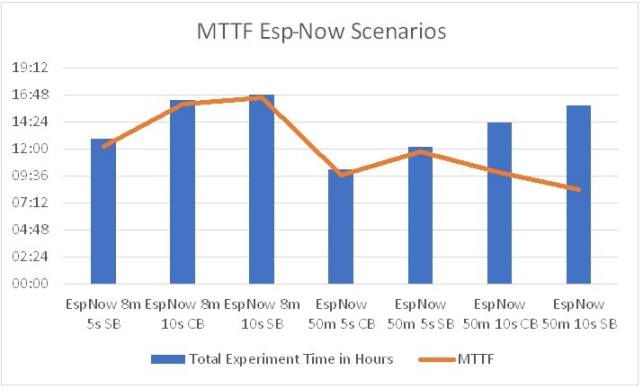

Figure 2: MTTF for ESP-NOW Scenarios

1.0.3 MTTF for Bluetooth Scenarios

Table 3 contains the average of the total experiment time from the four ESP32 present in each scenario and

the MTTF resulting from the calculation performed for Bluetooth technology.

Table 3 MTTF for Bluetooth Scenarios

Scenarios	Total Experiment Time in Hours	MTTF
BT 5 m 5 s BA	08:24:53	07:45:26
BT 5 m 5 s NB	09:59:13	09:13:42
BT 5 m 10 s BA	15:29:00	10:17:49
BT 5 m 10 s NB	16:30:00	08:53:00
BT 8 m 5 s BA	05:26:23	04:53:06
BT 8 m 5 s NB	06:24:13	05:50:23
BT 8 m 10 s BA	13:10:00	11:03:09
BT 8 m 10 s NB	14:27:00	10:00:11

Analyzing Figure 3 that presents the MTTF graph for the Bluetooth scenario, it is possible to identify that the 10 s experiments have a short MTTF, both for 5 m and 8 m. Thus, distance is not a factor impacting this Bluetooth technology index. When the graphs presented in Figures **??** and **??** (respectively Markov and Standard Deviation) are analyzed together, it is possible to verify that exists a large oscillation between the states presented by the Stochastic matrix, in addition to a significant variation in the standard deviation in the state (L). The 2.8 V failure rate appeared a few hours before stopping transmission.

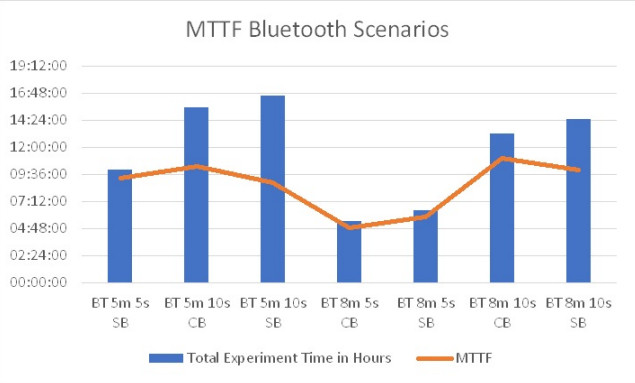

Figure 3: MTTF for Bluetooth Scenarios

1.0.4 Kaplan-Meier Analysis for 50 m ESP-NOW and Wi-Fi Scenarios

The graph presented in Figure 4 represents the stratification of the data analyzed in the ESP-NOW and Wi-Fi scenarios in the 50 m experiments with 5 s and 10 s with and without barrier.

The survival lines for the Wi-Fi scenarios identify that when the voltage reaches the limit of 2.8 V, it has a quick drop in a short time. Besides, it is also possible to verify that the time it remains in a state considered optimal or good, states (F) and (M), is very short concerning state (L).

In ESP-NOW scenarios, there are two different situations. The first is that in 5 s experiments with and without barrier, when the first 2.8 V status happens, a step in the form of a drop occurs. The explanation is that, from that moment on, the battery exhaustion is fast. In the 10 s experiments, this does not happen, the

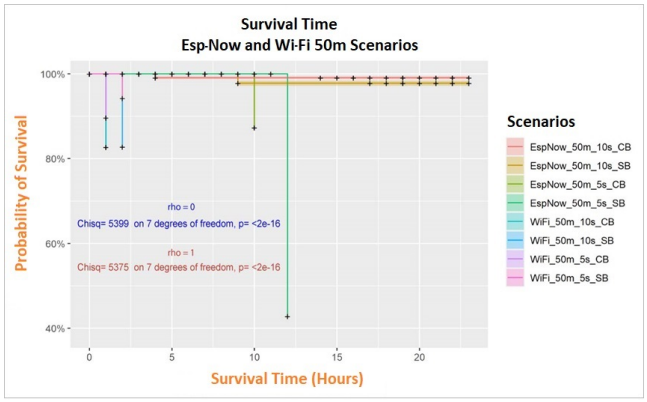

Figure 4: Kaplan-Meier 50 m ESP-NOW and Wi-Fi Scenarios

step is not accentuated, and the voltage oscillations stay in the line that remains above 90% during most of the test, generating a large oscillation from the state (M) to the end, as can be seen by the + signs on the chart.

Another interesting point is that even though the lines seem very close in the graph, the log-rank and Peto tests show that the value of p = < 2e-16 is less than 5%, indicating that there is a significant difference between the groups.

With the analysis of the Kaplan-Meier survival curve and the log-rank and Peto tests, it is possible to identify that the natural charging of the battery, generated by the increase in the interval, reflects the excellent performance of the ESP-NOW technology.

1.0.5 Kaplan-Meier Analysis of 8 m Bluetooth, ESP-NOW and Wi-Fi Scenarios

The 5 graph brings the survival curves of the Bluetooth, ESP-NOW, and Wi-Fi scenarios with the 8 m experiments; this graph shows the three scenarios because they all have a distance of 8 m in their experiments.

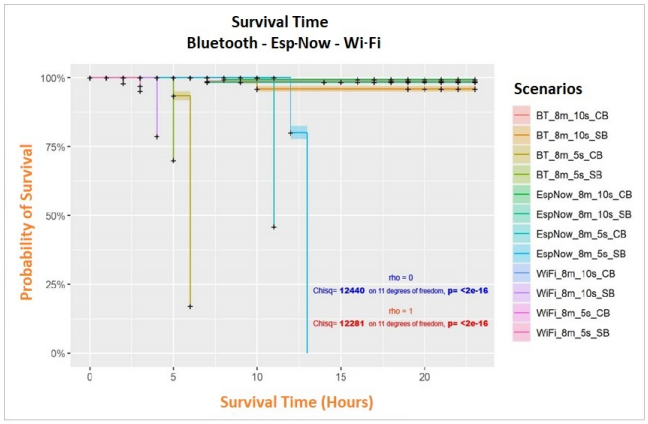

Figure 5: Kaplan-Meier Bluetooth, ESP-NOW and Wi-Fi Scenarios

The behavior of 10 s experiments in ESP-NOW and Bluetooth technologies are very similar, however, ESP-

NOW technology has a slight advantage in experiment survival. This can be verified in the analysis of the line corresponding to the BT 8 m 10 s NB scenario, which, a little before 10 hours of experiment, presents the first value of 2.8 V and thus has its first step. Soon after, at 10 h, it has a new step, while in the other experiments of 10 s, there is the occurrence of only one step. Again, the 10 s factor made a difference in the survival of the scenarios.

The log-rank and Peto tests show that the value of $p = < 2e\text{-}16$, in both tests, less than 5% indicates a significant difference between the groups, even though the curves seem to be close.