# Analysis of Energy Consumption Reliability in IoT Network

## 1 Appendix Markov

A Markov matrix helps to group the probabilities of transitions between the states of a given process. This appendix discusses the results obtained from the analysis of the Markov matrix for scenarios with Wi-Fi, ESP-NOW, and Bluetooth.

### *1.0.1 Markov Stochastic Matrix in Wi-Fi Scenarios*

Based on the data obtained from each of the sensors in the Wi-Fi experiment scenarios, Table 1 shows the average of the probabilities for transitions (or not) of states.

**Table 1** Markov Stochastic Matrix in Wi-Fi Scenarios

| 2° | 2° Wi-Fi 8 m 5 s BA | 2° Wi-Fi 8 m 5 s NB | 2° Wi-Fi 50 m 5 s BA | 2° Wi-Fi 50 m 5 s NB | 2° Wi-Fi 8 m 10 s BA | 2° Wi-Fi 8 m 10 s NB | 2° Wi-Fi 50 m 10 s BA | 2° Wi-Fi 50 m 10 s NB |
|---|---|---|---|---|---|---|---|---|
| **FF** | 0.99166015 | 0.99321391 | 0.92139283 | 0.94075163 | 0.99497678 | 0.99555879 | 0.91226254 | 0.938997821 |
| **FM** | 0.00833985 | 0.00678609 | 0.07860718 | 0.05924837 | 0.00502322 | 0.00444121 | 0.08773746 | 0.061002179 |
| **MF** | 0.25409284 | 0.24715114 | 0.17058536 | 0.10672735 | 0.49285515 | 0.40973524 | 0.227455622 | 0.150541425 |
| **MM** | 0.74532873 | 0.75239757 | 0.82369254 | 0.88928149 | 0.50588803 | 0.58854893 | 0.756601135 | 0.843731137 |
| **ML** | 0.00057843 | 0.00045129 | 0.0057221 | 0.00399116 | 0.00125683 | 0.00171583 | 0.015943243 | 0.005727437 |
| **LM** | 0.76152456 | 0.75718544 | 0.80970661 | 0.74791146 | 0.73144509 | 0.78313055 | 0.655563925 | 0.694307754 |
| **LL** | 0.23847544 | 0.24281456 | 0.19029339 | 0.25208854 | 0.26855491 | 0.21686945 | 0.344436075 | 0.305692246 |

With the graph of Figure 1, it is possible to analyze the transition between the states of the stochastic matrix. This visualization is generated from Table 1; however, as the values of the (FM) and (ML) states are irrelevant, they are not part of this graph.

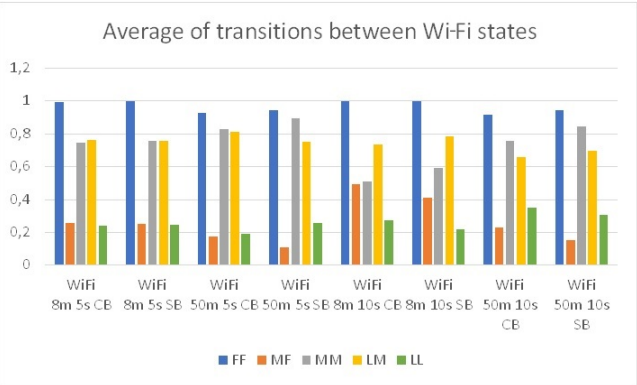


**Figure 1**: Average of transitions between Wi-Fi states

Throughout the study, some patterns are observed in the transitions. The scenarios are almost equivalent in the experiments with an interval of 5 s and 8 m of distance. However, the analysis of the same 5 s with 50 m shows a slight difference when applying the barrier factor. Despite being small, this variation is perceived in the rate of permanence in the (MM) state and in the transition between (LM), which are the most predominant states after (FF). In the 10 s with 8 m experiments, there is a more significant occurrence of (MF) and closeness to the events of (MM). It's important to point out that in this configuration, the (LM) transition surmounts the permanence in the (MM).

In general, the differences in the results of the average probability of permanence or change of states are very similar among the experiments. The differences are subtle. However, a slight stability trend in the states in the barrier-free experiments can be highlighted. Small stability in the permanence of the states can also be seen in the 10 s interval experiments, mainly in the (MM) and (LL) states. Natural charging explains this last result the battery suffers when packets are sent in shorter intervals.

### *1.0.2 Markov Stochastic Matrix in ESP-NOW Scenarios*

Table 2 has the overall average of state transition percentages for each experiment in the ESP-NOW scenario.

**Table 2** Markov Stochastic Matrix in ESP-NOW Scenarios

| | ESP-NOW 8 m 5 s BA | ESP-NOW 8 m 5 s NB | ESP-NOW 8 m 10 s BA | ESP-NOW 8 m 10 s NB | ESP-NOW 50 m 5 s BA | ESP-NOW 50 m 5 s NB | ESP-NOW 50 m 10 s BA | ESP-NOW 50 m 10 s NB |
|---|---|---|---|---|---|---|---|---|
| **FF** | 0.99106739 | 0.99338856 | 0.99106739 | 0.99937219 | 0.99282438 | 0.9929183 | 0.98805218 | 0.99394431 |
| **FM** | 0.00893262 | 0.00661144 | 0.00893262 | 0.00062781 | 0.00717562 | 0.00701817 | 0.01194782 | 0.00605569 |
| **MF** | 0.00229076 | 0.00268048 | 0.00229076 | 0.38211928 | 0.0023708 | 0.00253771 | 0.63347387 | 0.62695675 |
| **MM** | 0.99759181 | 0.99721533 | 0.99759181 | 0.61758461 | 0.99749701 | 0.99735406 | 0.36632105 | 0.37285517 |
| **ML** | 0.00011744 | 0.00010419 | 0.00011744 | 0.00029612 | 0.00013218 | 0.00010823 | 0.00020509 | 0.00018809 |
| **LM** | 0.27486729 | 0.20645049 | 0.27486729 | 0.5025015 | 0.51864848 | 0.26011149 | 0.5961971 | 0.47829894 |
| **LL** | 0.72513271 | 0.79354951 | 0.72513271 | 0.4974985 | 0.48135153 | 0.73988851 | 0.4038029 | 0.52170106 |

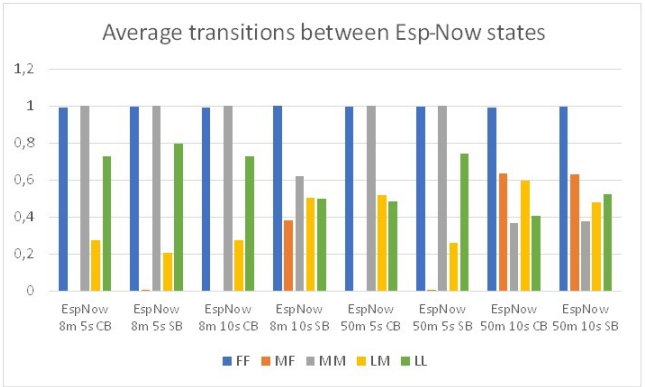


**Figure 2**: Average of transitions between ESP-NOW states

With the graph shown in Figure 2, a more comprehensive analysis of the transition between the states of the stochastic matrix is possible. This

visualization was generated from Table 2; the (FM) and (ML) state values are not displayed in this graph, as they are irrelevant.

In experiments with the ESP-NOW technology, transitions between states also follow a similar pattern. Figure 3 shows that the (MF) transition practically disappeared in the experiments with an interval of 5 s. In comparison, it is highlighted in the experiments of 10 s, except in the ESP-NOW 8 m 10 s BA scenario, which the presence of barriers may have influenced.

The conclusion is that the natural charging of the battery and the applied distance for ESP-NOW technology increases the probability of switching between states, especially the (MF) state, with a slight decrease in stability in the (MM) state.

### *1.0.3 Markov Stochastic Matrix in Bluetooth Scenarios*

Table 3 shows the average of the state transition probabilities for all experiments, while the graph presented in Figure 3 shows these values in the form of bars, except the values of the (FM) and (ML) states that are irrelevant.

**Table 3** Markov Stochastic Matrix in Bluetooth Scenarios

| | Bluetooth 5 m 5 s BA | Bluetooth 5 m 5 s NB | Bluetooth 5 m 10 s BA | Bluetooth 5 m 10 s NB | Bluetooth 8 m 5 s BA | Bluetooth 8 m 5 s NB | Bluetooth 8 m 10 s BA | Bluetooth 8 m 10 s NB |
|---|---|---|---|---|---|---|---|---|
| **FF** | 0.98902195 | 0.99165496 | 0.99968034 | 0.99962399 | 0.98615355 | 0.98947253 | 0.99964348 | 0.99967549 |
| **FM** | 0.01097805 | 0.00834504 | 0.00031966 | 0.00037601 | 0.01384645 | 0.01052747 | 0.00035653 | 0.00032451 |
| **MF** | 0.00212564 | 0.00237258 | 0.54699278 | 0.59902697 | 0.00937161 | 0.00571288 | 0.40132459 | 0.37778571 |
| **MM** | 0.99771081 | 0.99748973 | 0.45241749 | 0.40057328 | 0.99032428 | 0.99403252 | 0.59810086 | 0.62167296 |
| **ML** | 0.00016355 | 0.00013769 | 0.00058973 | 0.00039975 | 0.0003041 | 0.0002546 | 0.00057455 | 0.00054134 |
| **LM** | 0.39231941 | 0.34215529 | 0.82708956 | 0.55181773 | 0.38925148 | 0.51461339 | 0.67405063 | 0.59211335 |
| **LL** | 0.60768059 | 0.65784471 | 0.17291044 | 0.44818227 | 0.61074852 | 0.48538661 | 0.32594937 | 0.40788665 |

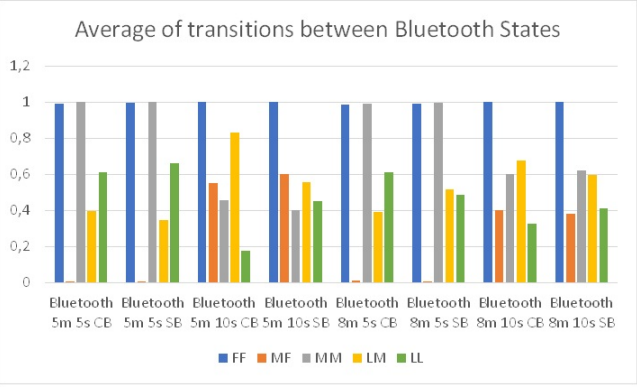


**Figure 3**: Average of transitions between Bluetooth states

In the 5 s experiments, there is almost no variation for the (MF) state, so stability in the (MM) state is predominant. However, it is interesting to note that in the experiments with intervals of 10 s, the transition between the (MF) state occurs, showing the influence of the natural recharge of the battery.

The scenarios with Bluetooth technology are quite similar in terms of permanence or variation between states. It is the study with more convergent points, and when the 10 s interval is applied, the (MF) variation increases. An important factor is that the ESP32 is designed with Low-Energy Bluetooth technology; that is, the internal control of the ESP32 optimizes these transitions to ensure battery savings.