Analysis of Energy Consumption Reliability in IoT Network

1 Appendix Standard Deviation

Standard deviation is one of the most commonly used statistical measures to demonstrate data variability. This appendix discusses the standard deviation results obtained with Wi-Fi, ESP-NOW, and Bluetooth technologies.

1.1 Standard Deviation in Wi-Fi Scenarios

Table 1 and Figure 1 show the average of the standard deviations obtained in each of the scenarios of the experiments, considering the battery levels and the configuration of each of the eight scenarios presented.

Table 1 Standard Deviation in Wi-Fi Scenarios

2*	Wi-Fi 8 m 5 s BA	Wi-Fi 8 m 5 s NB	Wi-Fi 8 m 10 s BA	Wi-Fi 8 m 10 s NB	Wi-Fi 50 m 5 s BA	Wi-Fi 50 m 5 s NB	Wi-Fi 50 m 10 s BA	Wi-Fi 50 m 10 s NB
Full	0.04882611	0.04083042	0.02457534	0.02294022	0.10837344	0.06963249	0.08500778	0.04882213
Medium	0.01387447	0.01309216	0.01212694	0.0106218	0.0243017	0.01627573	0.0311771	0.02471764
Low	0.03999306	0.03050011	0.02558058	0.02563343	0.044427	0.0363086	0.05530553	0.03868872

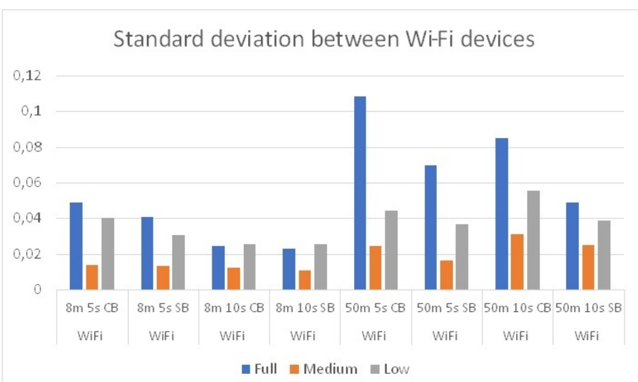

Figure 1: Standard deviation in Wi-Fi scenarios

As shown in Figure 1, the standard deviation applied in the Wi-Fi scenarios experiments shows stability in the readings with a distance of 8 m with intervals of 5 s and 10 s. However, there is more significant variability when the distance is 50 m with the same intervals. It is worth mentioning that all scenarios with intervals of 10 s between transmissions have more readings than scenarios of 5 s. This is due to the natural charging of the battery while it is in a standby state within 10 s. This is accentuated in the 50 m scenarios, with an increase in the standard deviation, mainly due to the high energy consumption characteristic of Wi-Fi. Scenarios with barriers show a slight increase in variability compared to non-barrier scenarios, which was already expected. Wi-Fi technology is known for consuming a large amount of energy for its transmission; however, when evaluating the data of 50 m with 10 s and 8 m with 10 s, it is noticed that even if the battery has some life survival since it recharges naturally, in 5 s intervals, this recharging can't stabilize, and the variability increases when the battery is in (M) or (L) state.

The analysis of Figure 1 shows more significant variability in states (F) and (L). However, in the 50 m and 10 s experiment, an average of 102 measurements were obtained in the state (F), 687 in the state (M), and 63 in the state (L). Even if the battery has a survival level, it cannot stabilize and have linearity since the states (L) of the two scenarios are very close. That is, almost the same number of readings are generated when distance is considered, but the variability is more pronounced.

1.1.1 Standard Deviation in ESP-NOW Scenarios

Table 2 shows the average obtained from the standard deviation readings of each experiment scenario, considering the battery levels and the configuration of each of the eight scenarios presented. The graph shown in the figure 2 illustrates the data in Table 2.

Table 2 Standard deviation in ESP-NOW Scenarios

2*	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
Full	0.0522422	0.0431662	0.02744364	0.0237409	0.04388618	0.04320531	0.05009534	0.03503264
Medium	0.0085003	0.0090736	0.02961053	0.026769	0.0081365	0.00784765	0.03152093	0.02820736
Low	0.0134925	0.0116699	0.03585295	0.0312875	0.01057636	0.00910229	0.04198575	0.03027889

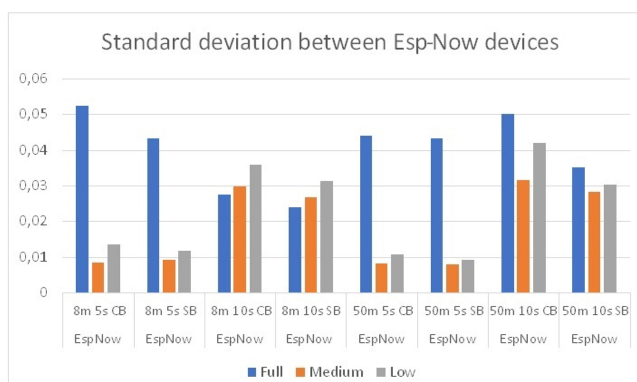

Figure 2: Standard Deviation in ESP-NOW Scenarios

In radio transmission using ESP-NOW technology, it is verified that the transmission interval generates more impact on the variability of the standard deviation than both distance and barriers.

The variability in Figure 2 becomes apparent when the influences of distance and barriers are isolated, and the focus is established at 5 s and 10 s. If the scenarios approaching all the 5 s and 10 s intervals are isolated, they are similar, but the point to be observed is the comparison between 5 s and 10 s.

The individual readings show that the 5 s experiment contains an average of 6,000 measurements, and the battery is more linear drained, discharging gradually until it changes state. However, in the 10 s experiments, there are about 9,000 measurements, and the standard deviation graph has very expressive curves and peaks. This is due to the natural recharge of the battery, which can recover in the time between transmissions, and thus provides indices of variations in measurements.

1.1.2 Standard Deviation in Bluetooth Scenarios

Table 3 also shows the mean of the standard deviations of the scenarios, and Figure 3 illustrates these results.

Table 3 Standard Deviation in Bluetooth Scenarios

2*	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
Full	0.0555929	0.0521544	0.0198413	0.0271968	0.067155	0.0625574	0.0203434	0.0201953
Medium	0.008201	0.0081368	0.0327593	0.041208	0.0195766	0.0247469	0.0422335	0.0448466
Low	0.0122696	0.0121403	0.0937307	0.0845579	0.0258559	0.0240346	0.0799658	0.0779746

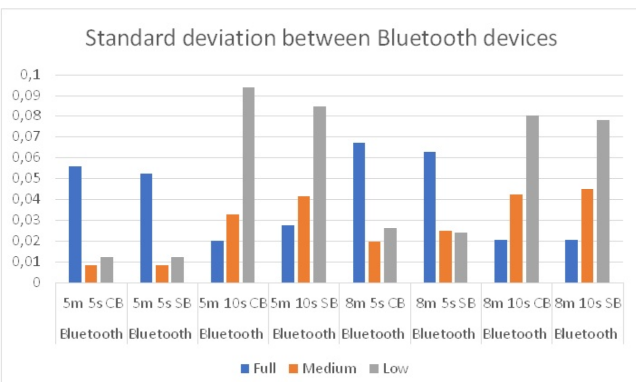

Figure 3: Standard Deviation in Bluetooth Scenarios

The standard deviation applied in the measurements of the Bluetooth technology shows stability in all experiments, either in the transmission intervals or in the used distance. The readings taken in the experiments with 5 s intervals have a higher variability when the charge is full. In experiments with an interval of 10 s, this increase in variability moves to the low charge level.

The reason is that with 5 s intervals, the sensors do not recharge due to the incessant traffic flow. This makes them lose power quickly when in the (F) state. Proof of this is that with 5 s, there are just a few measurements in the state (F): about 100 measurements (Appendix A - Spreadsheets of the data captured in the experiments - `https://github.com/rogeriobcosta/Documents_Article.git`) . The graphs show that this behavior, without time to recharge, increases the state standard deviation (F). The state (M), on the other hand, is what concentrates most of the measurements, between six and seven thousand measures (Appendix A - Spreadsheets of the data captured in the experiments - `https://github.com/rogeriobcosta/Documents_Article.git`). It is noticeable that the state (M) has low variability, as well as the state (L), which contains about 650 measurements.

In the 10 s experiment, the longer interval between transmissions allows the sensors to have a slight recharge, significantly increasing battery life and the number of measurements in the (F) state. In this case, the variability drops in the state (F). For states (M) and (L), the variability increases.

- For the 5 s interval, there is a relationship between the number of measurements and variability (they are inversely proportional: fewer measurements = more variability) with the high variability concentration in the state (F). This relationship between the number of measures and variability is maintained in the 10 s experiments, but it is concentrated in the states (M) and (L). The following facts cause this inverted proportionality: when the sensor battery is full, it loses power more sharply in shorter transmission intervals, i.e., 5 s, and does not allow natural battery recharge. This leads the state (F) to have fewer measurements and more variability;
- When the experiment has a longer interval, 10 s, the natural recharge of the battery between transmissions happens. This makes the (F) state have more measurements with less variability. The states (M) and (L) had few measurements and more variability. It can be said that in the experiment, while the battery had more charge, it was more likely to recharge itself naturally, a fact that augmented battery life and decreased variability. When the battery entered states (M) and (L), it did not recharge itself naturally as it did in the state (F). This led to decreased measurements and increased variability.

These conditions were repeated in experiments with distances of 5 m and 8 m. In addition, the barrier factor does not significantly influence Bluetooth, probably because it is a PAN network with short distances.