Fig. 5 shows the voltage if 3 diodes are connected in series to start with. It can be seen that the voltage at the storage reaches 3.8 volts after about 300 seconds.

We experimented with 2 different wireless systems based on the same hardware. Only the software needed to be modified.

1) *Proprietary wireless system*

In the first case, the radio was programmed in a proprietary mode. This is the mode requiring the smallest amount of energy. The payload was kept minimal and date transmitted as fast as possible. In that configuration, the energy consumption was less than 7µJ. The small amount of energy means that one could work with smaller storage elements. One could also send more frames per time unit or work with less light. The disadvantage is that a proprietary radio is required to receive the signal. In Fig. 10 it can be seen that with 4 LEDs and 250 lux, one harvests enough energy to send proprietary messages after 76 seconds. At 1000 lux, the message frequency increases to 1 after 23 seconds (Fig. 11)

2) *Ble compatible ADV frames*

In the second case, the frames used are compatible with Bluetooth Smart and can therefore be received on a smartphone or any other device equipped with that wireless standard. The energy consumption is higher and a larger storage capacitor is required. The system will also need more light. Fig. 6 shows the energy consumption of the wireless system in the best case of a low constant voltage (about 2 volts).

The voltage delivered by the storage element to the load is not really constant. The storage element is a capacitor. This means that the system must be so designed that the capacitor has enough energy for the load as it discharges. The lowest Vdd should not be lower that the VDDmin of the embedded system. Consequently, the energy consumption of the whole system is higher, than the best case. More energy must therefore be harvested.

With 4.5v on 1µF, the accumulated energy is about 10µJ. That is 8µJ available between 4.5v and 2v. This was enough to transmit a proprietary frame. But this is not enough for the Ble frames. Increasing the luminosity to 1000 lux allowed us to harvest faster. This will be good enough in some buildings.

For Ble compatible frames, more energy was needed in the storage. We used a 10µF capacitor. Loading the capacitor at 4.5 volts will yield about 100µJ. Of this energy, 80µJ can be used between 4.5v and 2v. This is enough to send 1 to 3 ADV frames.

Fig. 7 shows the energy consumption of the system when the energy is not sufficient. Here in the case of Ble. It can be clearly seen that the voltage breaks down after the radio starts sending. The frame is only partly transmitted, resulting in a CRC error.

Fig. 8 shows the whole system consumption when one Ble frame is properly transmitted.

Using the 10µF capacitor and working at 1000 lux, it was possible to send a message after 114 seconds (Fig. 9).

V. COSTS

For outdoor applications, 4 diodes connected in series will be enough. Their cost is well below that of a CR2032 with battery holder. However, the circuit also needs a low power isolation circuit to allow energy to be stored. We estimate that costs around $1 with the EH and associated electronics are possible, making the system competitive for the kind of applications described here.

VI. CONCLUSIONS

We demonstrated a very low-cost battery-less node powered by LEDs. The system has the potential to compete in price with battery based systems. It can last longer, (beyond the guaranteed lifecycle of batteries). It is smaller (compared to a standard system based on a CR2032) and more robust. As disadvantage, it can be used only where there is sufficient light (typically 600 lux or more with the appropriate spectral content). It is also for applications where communication is only needed at intervals of tens of seconds, so as to allow the accumulation of enough energy.

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