

Sizing Photovoltaic Harvesters for Energy-Neutral UWB Sensors in Space

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Abstract—Impulse radio ultra-wideband (IR-UWB) radios suit intra-spacecraft sensor networks through their multipath robustness and precise ranging capability, but the high peak currents of commercial transceivers strain the small photovoltaic harvesters and supercapacitor buffers practical in space, where lithium cells are poorly suited to the often unconditioned thermal envelope. We derive a temperature aware loss model for energy-neutral UWB nodes that provides a single design equation for the minimum photovoltaic area $A_{PV,min}(D, E_e, T)$. Calculation requires the dominant standing loss, supercapacitor self discharge, which we measure to rise $\approx 2.6\times$ between 25°C and 50°C . The resulting sizing curves show a plateau dominated by leakage current and a slope defined by the energy per transmit burst. For a cadence of one packet per minute under 0.6 W m^{-2} , an ADP5091/DW3000 based prototype's 10.66 cm^2 cell is able to sustain operation at 25°C with $\approx 16\%$ margin but falls $\approx 25\%$ short at 50°C , showing how strongly temperature drives harvester sizing.

Index Terms—Ultra-wideband, wireless sensor network, energy harvesting, photovoltaic, supercapacitor, space avionics, harsh environment.

I. INTRODUCTION

Modern spacecraft carry a growing number of distributed sensors whose wiring adds a significant share to the overall harness mass and integration effort. Wireless links remove much of this burden, with surveys of wireless avionics intra-communication quantifying the harness savings that motivate the transition to these kind of systems [1]. Among the candidate radio technologies, impulse-radio ultra-wideband (IR-UWB) is especially well suited to a spacecraft interior: its wide bandwidth gives robustness to the dense multipath of metallic cavities, it provides accurate ranging on centimeter level, and its low power spectral density limits interference with co-located avionics [2].

Energy harvesting addresses the problem that wireless sensors still need wiring for supply, but the storage element must survive the same harsh environment. Lithium cells, despite their energy density, are poorly matched to the unconditioned thermal envelope of many intra-spacecraft locations. Electric double-layer capacitors (EDLCs or “supercapacitors”) instead offer a far wider operating temperature range and effectively unlimited cycling, making a photovoltaic harvester feeding a supercapacitor an attractive supply at the price of higher self-discharge.

Commercially available IR-UWB transceivers draw tens of milliamperes while active, complicating the design of such systems. Prior work on energy harvesting UWB networks

has relied on custom ultra-low-power silicon or event-driven duty cycling, and to our knowledge no systematic study ties photovoltaic area, supercapacitor behaviour, and temperature together for a commercial-transceiver-class node under space-relevant low-light conditions. This paper provides that sizing guidance.

Contributions:

- A temperature-aware loss model for a PV-and-supercapacitor UWB node that comes down to a single design equation, $A_{PV,min}(D, E_e, T)$, for the minimum photovoltaic area for energy-neutral operation.
- A measured Arrhenius characterization of EDLC self-discharge across 25°C to 50°C , supplying a term usually absent from datasheets.
- PV-area sizing curves spanning a low light reference of 0.6 W m^{-2} up to the AM0 space solar irradiance (1361 W m^{-2}), validated against an ADP5091/DW3000-class prototype.

II. RELATED WORK

Wireless intra-vehicle networking is motivated mainly by the mass and harness savings it offers over traditional wired avionics. Park *et al.* [1] survey wireless avionics intra-communications and quantify the amount of wiring that wireless links can replace, a finding that can also be transferred to spacecraft. Within spacecraft and launchers, IR-UWB has been studied both at the PHY level inside a metallic satellite mockup, where stable links were shown despite strong multipath [2], and as a complete in-orbit sensor network aboard the ISS that additionally evaluated internal light sources for energy harvesting [3].

At the node level, energy harvesting for UWB has so far been pursued mainly with custom, ultra low-power CMOS pulse transmitters. Kim *et al.* [4] integrate solar harvesting and an 8 GHz UWB transmitter into a 10.6 mm^3 node, and Benamrouche and Dragomirescu [5] report an energy efficient IR-UWB transceiver for autonomous sensor networks. Both rely on autonomous harvesting frontends of the kind analyzed by Romani *et al.* [6].

Closest to the present work, commercial DW3000 class transceivers have recently been operated from harvested energy: Mayer *et al.* [7] demonstrate a self-sustaining UWB positioning tag validated over 700 days, while Flueratoru *et al.* [8] quantify the comparatively high power demand of these

high pulse rate (DW1000/DW3000 class) UWB transceivers. These works adopt *event-driven* duty cycling rather than sizing the system for constant rate operations. To the best of our knowledge no prior study systematically measures the $A_{PV} \times C \times \text{MAC} \times T$ sizing for the class of commercial IR-UWB transceivers under low-light and space conditions.

III. HARVESTING CHAIN AND LOSS MODEL

The harvesting chain considered in this work consists of a photovoltaic cell feeding a boost converter harvesting IC that charges a supercapacitor buffer, which in turn supplies a regulated rail to the MCU and the UWB transceiver. Electric double-layer capacitors tolerate the wider thermal envelope and effectively unlimited charge/discharge cycles [9].

For sustained operation the average harvested power must cover both the standing system losses and the duty cycled energy of UWB transmissions. This is captured by the energy neutrality inequality [10]

$$P_{harv} \eta_{store} \geq P_{drain} + D(E_{tx} + E_{oh}) \quad (1)$$

where P_{harv} is the average raw PV output power, η_{store} is the harvest chain efficiency (MPPT and boost stages of the harvester IC), P_{drain} is the standing power continuously drawn from the buffer (IC quiescent current plus supercapacitor leakage), D is the transmission rate in transmissions per second (s^{-1}), E_{tx} is the radio energy of a complete UWB transmission burst, and E_{oh} is the energy of the surrounding MAC layer and MCU processing overhead (CSMA-CA back-off, header transmission, acknowledgement processing).

In addition to the power flows described in (1) an additional one is required to account for the efficiency of the power rail regulator that draws from the buffer and its efficiency η_{reg} . The resulting nodes power rail energy per burst can be written as

$$E_{req} = \frac{E_{tx} + E_{oh}}{\eta_{reg}} \quad (2)$$

In what follows V_{sys} denotes the supercapacitor voltage. For conservative numerical estimates it is evaluated at its upper rail V_{start} .

1) *Supercapacitor sizing*: The buffer operates between two voltage rails: an upper rail V_{start} set by the harvester output and the capacitor's rated voltage, and a lower rail V_{end} set by the regulator's input under voltage lockout. Sizing it to be able to carry N bursts plus the standing loss P_{drain} over a holdover time t_{hold} of no harvesting available, $E = \frac{1}{2}CV^2$ gives

$$C_{min} = \frac{2(N E_{req} + P_{drain} t_{hold})}{V_{start}^2 - V_{end}^2} \quad (3)$$

with a single burst represented by $N=1$, $t_{hold}=0$. The physical buffer is then sized above C_{min} to provide margin for ESR-induced voltage sag during the active bursts, capacitance loss with aging, and component tolerance [9], [11].

2) *Effective harvested power*: A PV cell operating at its maximum-power point produces a raw electrical power $P_{raw} = V_{PV} I_{PV}$. Two loss factors have to be taken into account before energy reaches the storage element. The MPPT controller periodically interrupts power transfer to resample the maximum power point, contributing a duty cycle factor η_{MPPT} set by the harvester IC's sampling schedule. The boost converter contributes a conversion efficiency η_{boost} that depends on input voltage and load [6], [12]. The effective power reaching the supercapacitor is therefore

$$P_{harv,eff} = V_{PV} I_{PV} \eta_{MPPT} \eta_{boost} \quad (4)$$

which identifies the harvesting efficiency of (1) as $\eta_{store} = \eta_{MPPT} \eta_{boost}$.

3) *Standing losses*: Two terms drain the storage element continuously, independently of any active transmissions. The harvesting IC quiescent current I_Q contributes $P_{IQ} = I_Q V_{sys}$ [6]. The supercapacitor's self discharge current $I_{leak}(T)$, where T denotes the ambient node temperature (in $^{\circ}\text{C}$), is strongly dependent on ambient temperature [11], [13], [14] and is characterised in Section V. It contributes $P_{leak} = I_{leak}(T) V_{sys}$. The harvester quiescent current I_Q and the conversion efficiencies η_{MPPT} , η_{boost} , η_{reg} are taken as temperature independent over the range considered. The total standing power is

$$P_{drain}(T) = (I_Q + I_{leak}(T)) V_{sys} \quad (5)$$

4) *Net charging power and sustainable duty cycle*: The net rate at which energy accumulates in the buffer is

$$P_{net}(T) = P_{harv,eff} - P_{drain}(T) \quad (6)$$

and the minimum interval between two transmissions for energy-neutral operation is

$$\tau_{tx,min} = \frac{E_{req}}{P_{net}(T)} \quad (7)$$

or equivalently a maximum sustainable transmission rate $D_{max} = 1/\tau_{tx,min}$.

5) *Main Sizing Equation*: Combining the models above yields the central design equation of this paper. Treating the PV cell as approximately linear in irradiance E_e (W m^{-2}) over its operating range [15], with an overall conversion efficiency η_{PV} , the effective power delivered to the buffer is $P_{harv,eff} = E_e \eta_{PV} \eta_{MPPT} \eta_{boost} A_{PV}$. Substituting into the other equations and solving for area gives the sizing contribution of this work:

$$A_{PV,min}(D, E_e, T) = \frac{P_{drain}(T) + D E_{req}}{E_e \eta_{PV} \eta_{MPPT} \eta_{boost}} \quad (8)$$

Equation (8) summarizes the design problem into three measurable groups of terms: the standing buffer loss $P_{drain}(T)$ (temperature and supercapacitor choice), the per transmission burst energy required $E_{req} = (E_{tx} + E_{oh})/\eta_{reg}$ (MAC protocol, MCU and radio configuration) and the environment/traffic rate pair (E_e, D) . The denominator reduces to a single constant once a harvester chain is selected. The

experimental section branches (8) into a family of sizing curves $A_{PV,min}(D, E_e, T)$ that provide a design guidance for the target system. When mechanical constraints fix area rather than throughput, the same input values can be used to calculate the minimum transmission interval $\tau_{tx,min}$ via (7).

IV. VERIFICATION ON ADP5091 BASED PROTOTYPE

This section instantiates the abstract model of section III on prototype hardware used in this work, in order to provide the parameter sweeps presented later with a concrete numerical reference point. The prototype is built around an Analog Devices ADP5091 boost converter harvesting IC fed by a small low-light photovoltaic cell (AMG-1401C). The ADP5091 charges an electric double-layer capacitor (EDLC) (Abracon ADCM-S05R5SA224XB) buffer of 0.22 F, which in turn feeds to a regulated 3 V rail supplying the MCU and a DW3000 based IR-UWB transceiver. The following subsections first provide the temperature characterization of the chosen capacitor and then apply the equations from section III to this hardware.

A. Capacitor Temperature Characterization

The supercapacitor self discharge current is the single largest standing loss of the system: at room temperature it already exceeds the harvester quiescent current I_Q by nearly an order of magnitude (cf. Eq. (5)) and it is the only temperature dependent part of the loss model. Quantifying its growth with ambient temperature is therefore a prerequisite for evaluating the sizing equation (8) at the varying temperatures typical of unconditioned intra-spacecraft locations. The prototype EDLC offers a datasheet leakage of $4 \mu\text{A}$ at room temperature (25°C). As is common for this device class, manufacturer data on the *temperature* dependence of leakage is sparse and generally absent from the part datasheets, which motivates the characterization reported in other sources as well [13], [14].

1) *Method*: Prior to measurement the devices under test (DUTs) are pre-conditioned for 72 h at their rated voltage. This fully wets the electrolyte and lets the charge redistribute uniformly over the electrode area, so that the slow charge redistribution transient that occurs in EDLCs does not surface as an elevated steady state leakage [11]. The leakage is obtained the following way: each device is held at its rated voltage by a source-measure unit (SMU), and the current required to maintain that voltage is logged. The resulting value is the self discharge current I_{leak} . The samples sit in a temperature chamber whose ambient is stepped from 25°C to 50°C in 5°C increments. At each set point the device is allowed to reach combined thermal and electrical equilibrium for 2 hours prior to I_{leak} being recorded. Ten devices were measured per set point to capture manufacturing spread. At this microampere level Joule self heating of the EDLCs is negligible, so the recorded temperature is taken to be that of the chamber ambient. The measurement uncertainty per DUT is below $\approx 5\%$ and is therefore negligible when compared to the spread between DUTs, which is the visible scatter shown as the box-and-whisker graph in Fig. 1.

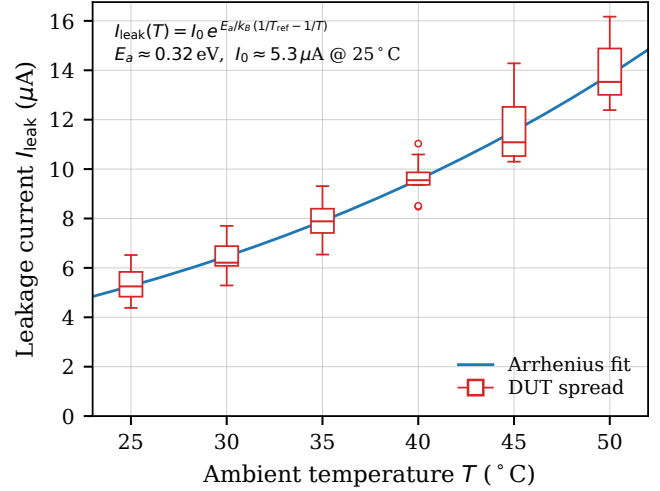


Fig. 1. EDLC leakage (self discharge) current versus ambient temperature for the 0.22 F prototype buffer. Boxes and whiskers: Spread between DUTs at each set point. Solid line: Arrhenius fit through all 60 individual measurements. The fitted $I_{leak}(T)$ provides the loss term $P_{leak} = I_{leak}(T) V_{sys}$ of Eq. (5).

2) *Result*: Figure 1 plots the measured leakage against ambient temperature. The data is fitted with an Arrhenius law $I_{leak}(T) = I_0 \exp[(E_a/k_B)(1/T_{ref} - 1/T)]$, used as an interpolation that provides a continuous $I_{leak}(T)$ for the loss model in place of a missing datasheet curve. Over the measured window the leakage rises monotonically by a factor of ≈ 2.6 , from a mean of $I_{leak}(25^\circ\text{C}) \approx 5.3 \mu\text{A}$ to $I_{leak}(50^\circ\text{C}) \approx 14 \mu\text{A}$ across the ten DUTs. The interquartile range between the DUTs broadens with temperature from $\approx 1 \mu\text{A}$ at 25°C to $\approx 2 \mu\text{A}$ at 50°C . The resulting fitted $I_{leak}(T)$ is the function substituted into the standing loss term $P_{leak} = I_{leak}(T) V_{sys}$ of Eq. (5). Because leakage dominates P_{drain} , the $\approx 2.6\times$ growth in leakage between 25°C and 50°C propagates to a $\approx 2.4\times$ growth in the overall standing buffer loss, and sets the temperature spread of the sizing curves analyzed in Section V.

B. Applying the Model

1) *Operating Point*: The nominal operating point of the prototype, used throughout the numerical examples in this section, is summarized in Table I. The active burst is modelled as a rectangular load of 21.6 mA drawn for 32 ms from a 3 V node rail, as has been measures on a hardware prototype, described in Section IV-C. The PV cell delivers 2.1 V at $35.4 \mu\text{A}$ at its maximum power point under the reference low light condition (reference irradiance $E_{e,ref} = 0.6 \text{ W m}^{-2}$ (standard indoor conditions of 200 lux), measured cell efficiency $\eta_{PV} = 0.116$, prototype cell area $A_{PV} = 10.66 \text{ cm}^2$). The reference condition is achieved by an LED light source set to 200 lx at the cell plane with a lux meter. η_{PV} is characterized at this point only (cf. Section III-5). The voltage window across which the buffer is operating is set by $V_{start} = 3.0 \text{ V}$ which is the ADP5091 system voltage set point and the EDLC's

TABLE I
PROTOTYPE OPERATING POINT USED IN THE WORKED EXAMPLE.

Symbol	Value	Description
V_{node}	3 V	Regulated node rail
I_{active}	21.6 mA	Active-burst mean current
t_{active}	32 ms	Active-burst duration
V_{PV}	2.1 V	PV MPP voltage
I_{PV}	35.4 μ A	PV MPP current
V_{start}	3.0 V	Upper buffer rail
V_{end}	2.5 V	Lower buffer rail
C	0.22 F	Populated EDLC
η_{reg}	0.91	Regulator efficiency
η_{MPPT}	0.984	ADP5091 MPPT duty factor
η_{boost}	0.89	ADP5091 boost efficiency
I_Q	760 nA	ADP5091 quiescent current
$I_{leak}(T_{room})$	5.3 μ A	EDLC leakage at room T
η_{PV}	0.116	PV optical-to-electrical eff.
$E_{e,ref}$	0.6 W m $^{-2}$	Reference irradiance
A_{PV}	10.66 cm ^{2}	Prototype PV area

rated voltage. The lower limit is set by $V_{end} = 2.5$ V, the regulator's input undervoltage lockout that is mandated by the voltage limits of the used components. The chain efficiencies and quiescent current are taken from the ADP5091 datasheet at the relevant operating point: $\eta_{reg} \approx 0.91$, $\eta_{MPPT} = 0.984$ (corresponding to the 1.6% loss defined by the ADP5091's 256 ms per 16 s MPPT sampling period), $\eta_{boost} \approx 0.89$ at low input voltages and quiescent current $I_Q \approx 760$ nA with the internal regulator enabled. The supercapacitor self discharge current at room temperature is $I_{leak}(T_{room}) \approx 5.3$ μ A for the used 0.22 F device. Its temperature dependence is characterized in section IV-A. For the conservative numerical estimates below, V_{sys} is always evaluated at V_{start} .

2) *Transmission Burst Energy Demand*: Evaluating the energy need at the operating point yields $E_{node} = V_{node} I_{active} t_{active} \approx 2.07$ mJ. With $\eta_{reg} \approx 0.91$, equation (2) gives a per-burst draw on the buffer of $E_{req} = E_{node}/\eta_{reg} \approx 2.28$ mJ.

3) *Buffer Sizing*: For a single burst ($N=1$, $t_{hold}=0$), substituting E_{req} together with $V_{start} = 3.0$ V and $V_{end} = 2.5$ V into (3) yields $C_{min} \approx 1.66$ mF. The prototype is populated with a standard 0.22 F cap. Inverting (3) for this device gives a holdover time. Its usable energy $\frac{1}{2}C(V_{start}^2 - V_{end}^2) \approx 0.30$ J covers $P_{drain}(T_{room}) \approx 18.2$ μ W for $t_{hold} \approx 4.6$ h of darkness before the regulator drops out.

4) *Effective Harvested Power*: At the example PV operating point, the raw electrical output is $P_{raw} = V_{PV} I_{PV} = 74.3$ μ W. Applying the harvester losses of (4) gives $P_{harv,eff} = P_{raw} \eta_{MPPT} \eta_{boost} \approx 65.1$ μ W, i.e. the ADP5091 chain delivers roughly 88% of the cell's raw output to the supercapacitor under these conditions.

5) *Standing Losses at Room Temperature*: With $V_{sys} = V_{start} = 3.0$ V and the quiescent/leakage currents from Table I, (5) evaluates to $P_{drain}(T_{room}) = (I_Q + I_{leak}(T_{room})) V_{sys} \approx 18.2$ μ W. The supercapacitor self discharge term dominates the harvester quiescent term by nearly

an order of magnitude. This shows that the temperature characterization of the capacitor is needed, since $I_{leak}(T)$ is expected to grow significantly at the elevated ambient temperatures typical of unconditioned spacecraft locations.

6) *Net Charging Power and Minimum Transmission Interval*: From (6) the net charging power available to refill the buffer between bursts is $P_{net}(T_{room}) = P_{harv,eff} - P_{drain}(T_{room}) \approx 46.9$ μ W, roughly a quarter of the raw harvested power is consumed by standing losses alone before any transmission takes place. The corresponding minimum interval between transmission from (7) is $\tau_{tx,min} = E_{req}/P_{net}(T_{room}) \approx 48.6$ s, i.e. approximately one transmission every 50 s, equivalent to a maximum sustainable transmission rate $D_{max} \approx 1.24$ min $^{-1}$. Under this low light condition the harvesting chain, not the radio's transmission burst energy, is the dominant constraint on throughput.

7) *Minimum PV Area at the Example Operating Point*: With the reference irradiance $E_{e,ref} = 0.6$ W m $^{-2}$ and the measured cell efficiency $\eta_{PV} = 0.116$ from Table I, the main sizing equation (8) reduces to a function of duty cycle alone. Taking as target transmission rate a rate of one packet per minute, $D_{ref} = 1$ min $^{-1}$, places the operating point at roughly 81% of the 25°C case or $D_{max} \approx 1.24$ min $^{-1}$, with the contribution $D_{ref} E_{req} \approx 38.0$ μ W per burst and the standing term $P_{drain}(T_{room}) \approx 18.2$ μ W. Substituting into (8) gives

$$A_{PV,min}(D_{ref}, E_{e,ref}, T_{room}) = \frac{P_{drain}(T_{room}) + D_{ref} E_{req}}{E_{e,ref} \eta_{PV} \eta_{MPPT} \eta_{boost}} \approx 9.2 \text{ cm}^2. \quad (9)$$

The prototype's used area of $A_{PV} = 10.66$ cm ^{2} therefore exceeds the minimum by roughly 16%, confirming that the hardware sits inside the energy-neutral envelope at room temperature and the chosen cadence. Re-evaluating (9) at 50°C, where $P_{drain} \approx 43.7$ μ W, raises the requirement to $A_{PV,min} \approx 13.4$ cm ^{2} , exceeding the populated area by about 25%: at the elevated supercapacitor leakage characterized in Section IV-A the cadence falls outside the prototype's envelope, and either the cell area, the transmission rate, or the thermal envelope would have to be adjusted. The full family of sizing curves $A_{PV,min}(D, E_e, T)$ generated from (8) is reported in Section V.

C. UWB Radio and MCU Subsystem

The radio subsystem is built around a DW3000 IR-UWB transceiver paired with a low-power MCU. High pulse rate (HRP) UWB transceivers of this class are comparatively power hungry, drawing on the order of tens of milliamperes while active [8]. Bench measurements on the prototype, summarized by the dashed mean in Fig. 2, place the time-averaged supply current of the active window at 21.6 mA drawn for 32 ms at the 3 V node rail. This justifies modelling the active burst as a rectangular 21.6 mA/32 ms load. Such a commercial transceiver trades energy efficiency for integration and standards compliance, in contrast to custom low-power IR-UWB transmitter designs that reach far lower active energy at the

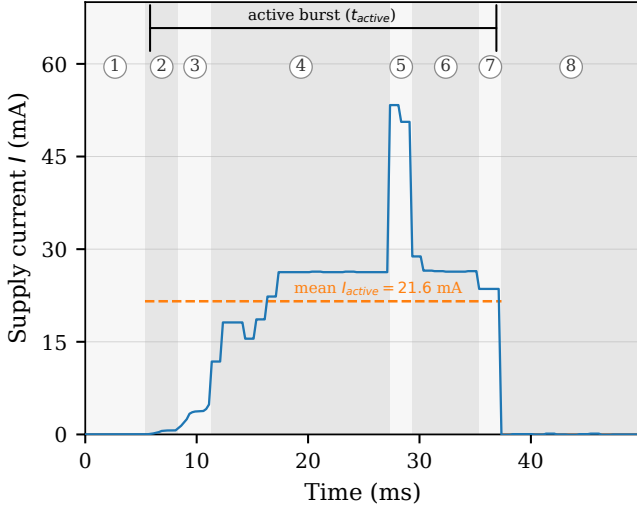


Fig. 2. Supply current waveform of the UWB radio and MCU through one TX transaction. Numbered stages: (1) sleep; (2) MCU wake-up, (3) transceiver power-on and PLL/clock lock, (4) MCU sensor reading and waiting for tx window, (5) TX burst, (6) post TX wait, (7) TRX and MCU peripheral power-down, (8) sleep, Dashed line: the mean of the active period ($I_{active} = 21.6$ mA) used in Section IV.

cost of needing bespoke silicon [5]. Figure 2 shows the current waveform of the radio and MCU subsystem through one transmit transaction. The transaction passes through a sequence of distinct power states: the node wakes from sleep, powers on the transceiver and locks its clock and PLL, performs sensor reads during a 10 ms guard interval, transmits the packet, holds an equal 10 ms post transmission guard for remaining MCU housekeeping, and finally powers down the radio and peripherals before returning to sleep, with each state drawing a significantly different current. The two 10 ms guard intervals are introduced in firmware to reserve room for sensor reading and other MCU tasks that a real-world deployment must perform within each active window. The radio's transmit burst proper accounts for the remainder of the 32 ms active period. The rectangular 21.6 mA approximation introduced above summarizes this into a single equivalent load that is used in (2) energy calculations.

V. RESULTS AND SIZING GUIDANCE

Figure 3 evaluates the sizing equation (8) for the verification prototype of Section IV ($E_{req} \approx 2.28$ mJ, $\eta_{PV} = 0.116$, $\eta_{MPPT} = 0.984$, $\eta_{boost} = 0.89$), at the two temperatures characterized in Section IV-A ($P_{drain}(25^\circ\text{C}) \approx 18.2 \mu\text{W}$, $P_{drain}(50^\circ\text{C}) \approx 43.7 \mu\text{W}$) [13], [14] and across four irradiance levels spanning the verification example low-light reference $E_{e,ref} = 0.6 \text{ W m}^{-2}$ up to the AM0 space solar irradiance 1361 W m^{-2} .

Each curve exhibits two regimes set by which term in the numerator of (8) dominates. For $D E_{req} \ll P_{drain}(T)$ the area required is set entirely by standing losses and is therefore *independent of duty cycle*. The flat plateau on the left of each curve. The temperature dependence of $A_{PV,min}$

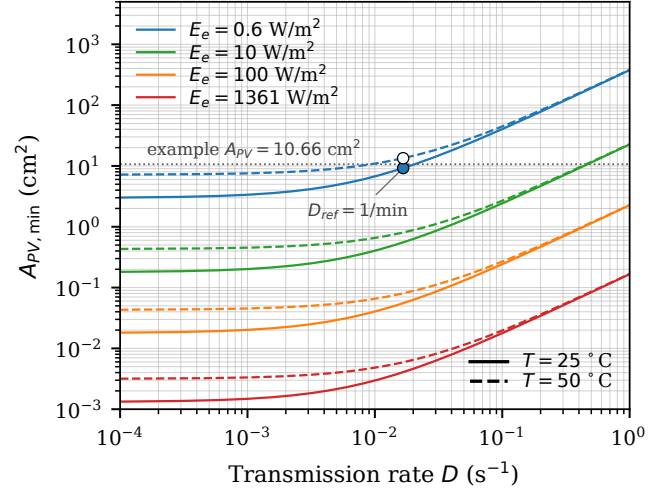


Fig. 3. Minimum photovoltaic area $A_{PV,min}$ for energy-neutral operation, plotted against transmission rate D for four irradiance levels (E_e) and two ambient temperatures (T). Solid lines: $T = 25^\circ\text{C}$ ($P_{drain} \approx 18.2 \mu\text{W}$); dashed lines: $T = 50^\circ\text{C}$ ($P_{drain} \approx 43.7 \mu\text{W}$). Computed from (8) with the verification example E_{req} and chain efficiencies. Dotted horizontal line: prototype populated area $A_{PV} = 10.66 \text{ cm}^2$. Filled and unfilled markers on the $E_e = 0.6 \text{ W m}^{-2}$ curves indicate the worked-example operating point ($D_{ref} = 1 \text{ min}^{-1}$) at 25°C and 50°C respectively.

is concentrated in this plateau: the required area scales with P_{drain} alone and therefore grows by the same $\approx 2.4\times$ factor as P_{drain} between 25°C and 50°C , whereas for $D \gg D_*$ the two temperatures become practically indistinguishable. The crossover where active and standing energy contribute equally falls at $D_* = P_{drain}(T)/E_{req} \approx 8.0 \times 10^{-3} \text{ s}^{-1}$ ($\approx 0.48 \text{ min}^{-1}$) at 25°C and $\approx 1.9 \times 10^{-2} \text{ s}^{-1}$ ($\approx 1.15 \text{ min}^{-1}$) at 50°C : above D_* all curves collapse onto a single, temperature-independent slope determined by the nodes energy need per burst and the only remaining influence on the required area is the irradiance.

This structure translates directly into sizing guidance. In the plateau supercapacitor leakage dominates the area budget, halving I_{leak} through a lower leakage part or thermal isolation yields a reduction in $A_{PV,min}$, while halving the cadence yields nothing. Above D_* the energy per burst and the available irradiance are the only levers. Reductions in E_{req} (a low power MAC or a lower radio bitrate) shift the slope down for every E_e in parallel. The verification example operating point ($E_{e,ref} = 0.6 \text{ W m}^{-2}$, $D_{ref} = 1 \text{ min}^{-1} \approx 1.67 \times 10^{-2} \text{ s}^{-1}$, marked on the lowest irradiation curves in Fig. 3) sits in this transition region. Reading the curves at this point gives $A_{PV,min} \approx 9.2 \text{ cm}^2$ at 25°C and $\approx 13.4 \text{ cm}^2$ at 50°C . The populated $A_{PV} = 10.66 \text{ cm}^2$ therefore covers the 25°C temperature case with $\approx 16\%$ margin but is exceeded by $\approx 25\%$ at 50°C . Meeting the required energy at the elevated temperature requires either dropping the cadence, or raising the available irradiance: at $E_e = 10 \text{ W m}^{-2}$ the same populated area sustains cadences more than an order of magnitude above D_{ref} and sunlit levels decouple the prototype entirely and it

is only limited by the radio's transmission burst energy.

VI. CONCLUSION AND FUTURE WORK

We asked whether a commercial transceiver based IR-UWB node can run energy neutrally from a small low-light photovoltaic cell and a supercapacitor in an unconditioned spacecraft environment. Providing a single design equation for the harvesting chain, $A_{PV,min}(D, E_e, T)$ of (8), reduces that question to three measurable groups of terms: the temperature dependent standing loss, the transmission burst MAC and radio energy, and the irradiance/traffic pair. This provides a family of sizing curves for the design with two parts: a plateau dominated by leakage and a slope defined by transmission energy burst above the crossover D_* , where node energy demand and irradiance are the only levers. Using the model requires supercapacitor self discharge temperature characterization, which is generally not available in their datasheets. Our Arrhenius characterization fit for the example shows it rising $\approx 2.6\times$ between 25°C and 50°C . The consequence is: at one packet per minute under 0.6 W m^{-2} , the prototype's 10.66 cm^2 cell meets the 25°C case ($\approx 9.2\text{ cm}^2$) with $\approx 16\%$ margin but falls $\approx 25\%$ short at 50°C . Energy-neutral UWB is thus feasible across a broad slice of intra-spacecraft conditions, but only when storage temperature is treated as a sizing parameter.

Several extensions follow. Adding the photovoltaic cell's negative temperature coefficient into a single combined thermal loss term would complete the model. Above D_* the energy E_{req} per transmission dominates, motivating measurement of lighter MAC variants to quantify how much of E_{oh} is recoverable in software. Finally, characterizing radiation induced leakage which is lacking in the current literature and longer term photovoltaic degradation measurements would extend this framework from a merely thermal viewpoint towards a full space qualification one.

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