A Total Energy Consumption Model

The total energy consumption of terminal devices originates mainly from two categories of tasks: external communication and local processing, expressed, respectively, as communication overhead E_{comm} and local overhead E_{local}. The total energy model is defined as

$$E_{\text{total}} = E_{\text{comm}} + E_{\text{local}}. \tag{1}$$

Here, E_{comm} includes energy consumed during data transmission/reception, protocol control, and secure communication; E_{local} includes local energy consumption such as processor operation, state maintenance, and system load.

A.1 Communication Energy Consumption Modeling

The energy consumption modeling of communication between the terminal and the gateway is fundamental for analyzing the energy distribution and optimizing energy efficiency. The total communication energy consumption is decomposed into four parts: transmission energy consumption, reception energy consumption, secure transmission energy consumption, and protocol control overhead.

A.1.1 Transmission Energy Consumption

For BFNs, transmission energy consumption is the major consumption when terminals send data to the gateway. The mathematical model is

$$E_{\text{tx}} = N \times \left((P_c + \eta \cdot P_{\text{te}}) \times \frac{L}{R} \right), \tag{2}$$

where N is the number of packets, L is the data size per packet (bits), and R is the transmission rate (bps). The circuit power P_c consists of a base power P_{base} and a dynamic power P_{mod} dependent on the transmission rate:

$$P_c = P_{\text{base}} + P_{\text{mod}}, \quad P_{\text{mod}} \propto R^{\beta} \quad (\beta \approx 1). \tag{3}$$

The effective transmit power P_{te} compensates for channel path loss:

$$P_{\text{te}} = \frac{\text{SNR} \cdot N_0 \cdot d^{\alpha}}{\eta \cdot h}, \tag{4}$$

where SNR is the signal-to-noise ratio, N_0 is the noise spectral density, d is the distance, α is the path loss exponent, h is the channel gain, and η is the amplifier efficiency:

$$\eta = \eta_{\max} \cdot \left(1 - e^{-\gamma P_{\text{te}}}\right). \tag{5}$$

Packet size L includes payload and protocol overhead:

$$L = \left(\left\lceil \frac{\text{size}}{\text{MTU}} \right\rceil \cdot B + \text{size} \right) \cdot 8. \tag{6}$$

Transmission rate R is modeled as

$$R = B \cdot \log_2 \left(1 + \frac{S}{N + N_{\text{interf}}}\right) \cdot C, \tag{7}$$

where S is signal strength, N is noise power, C is device capability, and N_{interf} represents interference.

A.1.2 Reception Energy Consumption

Reception energy consumption is modeled as

$$E_{\text{rx}} = N \cdot \left(P_{\text{rx}} \cdot \frac{L}{R}\right) + P_{\text{idle}} \cdot T_{\text{idle}}. \tag{8}$$

For passive nodes, the low-power listening (LPL) model is adopted:

$$E_{\text{rx}}^{\text{LPL}} = N \cdot \left(P_{\text{rx}} \cdot \frac{L}{R}\right) + (P_{\text{wake}} \cdot T_{\text{wake}} + P_{\text{sleep}} \cdot T_{\text{sleep}}) \cdot \frac{T_{\text{idle}}}{T_{\text{cycle}}}. \tag{9}$$

A.1.3 Protocol Control Overhead

Protocol control energy is modeled as

$$E_{\text{ctrl}} = N_{\text{ctrl}} \cdot \left(\frac{P_{\text{tx}} \cdot C}{R} + \frac{P_{\text{rx}} \cdot C}{R}\right) + E_{\text{proc}} \cdot N, \tag{10}$$

and optimized for intermittent nodes as

$$E_{\text{ctrl}}^{\text{LPL}} = N_{\text{wake}} \cdot \left[N_{\text{ctrl}}^{\text{per}} \cdot \frac{(P_{\text{tx}} + P_{\text{rx}}) \cdot C}{R} + E_{\text{proc}} \cdot N_{\text{ctrl}}^{\text{per}}\right]. \tag{11}$$

A.1.4 Secure Transmission Overhead

Secure transmission overhead is defined as

$$E_{\text{sec}} = N \cdot (E_{\text{enc}} \cdot L + E_{\text{dec}} \cdot L + E_{\text{auth}}), \tag{12}$$

and further optimized by energy-aware protocols:

$$E_{\text{sec}} = N \cdot (E_{\text{enc}}(l) \cdot L + E_{\text{dec}}(l) \cdot L + E_{\text{auth}}(l)). \tag{13}$$

A.2 Modeling of Local Processing Energy Consumption

For BFNs, local energy consumption includes both system load and efficiency of energy harvesting and storage. The system operates in three modes [**?**]: high-efficiency, low-power, and normal operation, as illustrated in Fig. 1.

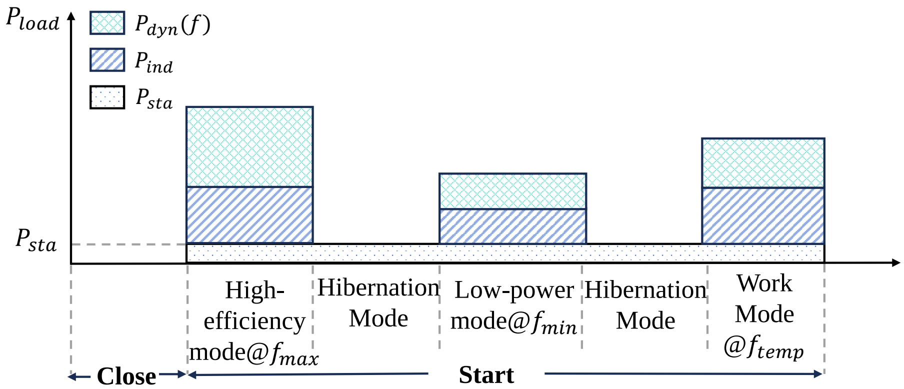

Figure 1: Power consumption in different modes of BFNs.

A.2.1 System Load Power Consumption

Load power consumption includes three types:

Frequency-dependent Power Consumption

$$P_{\text{dyn,sys}}(f) = \alpha C_{\text{eq}} V_{\text{op}}^2 f, \tag{14}$$

where α is the activity factor, C_{eq} the capacitance, and V_{op} the operating voltage.

Frequency-independent Power Consumption

$$P_{\text{ind}} = P_{\text{mem}} + P_{\text{IO}} + P_{\text{aux}}. \tag{15}$$

Static Power Consumption

$$P_{\text{sta}} = V \cdot I_{\text{leak}}. \tag{16}$$

A.2.2 Task Execution Time

Task execution time depends on parallel or serial processing.

Parallel Processing

$$T = \max\left(\frac{C}{f_{\text{cpu}}}, \frac{D_{\text{tx}} + D_{\text{rx}}}{B}, \frac{S}{R_{\text{sto}}}\right). \tag{17}$$

Serial Processing

$$T = \frac{C}{f_{\text{cpu}}} + \frac{D_{\text{tx}} + D_{\text{rx}}}{B} + \frac{S}{R_{\text{sto}}}. \tag{18}$$

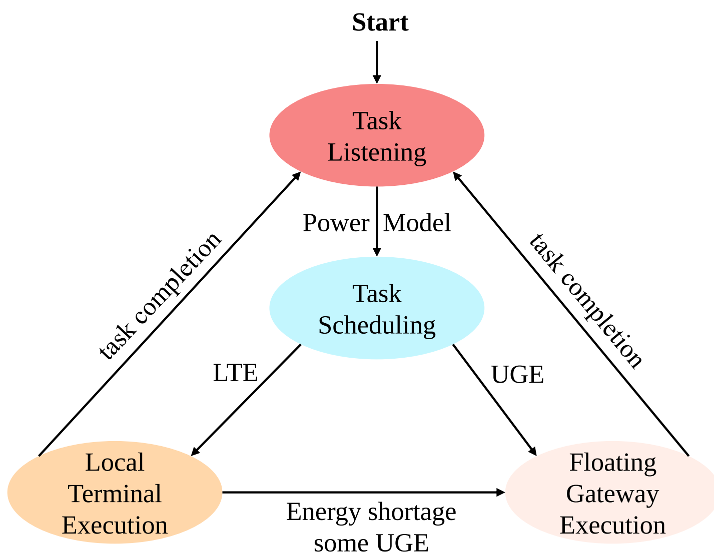

Figure 2: Adaptive task execution strategy under different energy levels.