Parameter-Aware Energy Models for Embedded-System Peripherals

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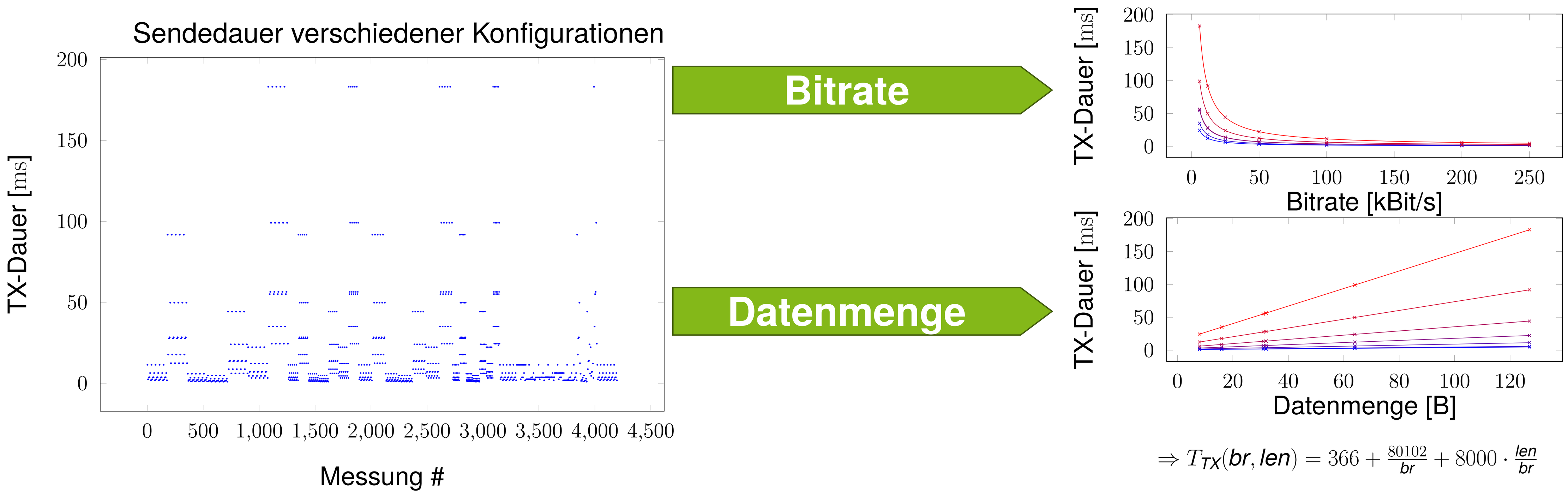
Goal: Detailed and reusable energy models for system peripherals

- Needed for transiently powered systems

Problem: Modeling is tedious and error-prone
Approach: Automatic model generation

- General-purpose energy models (independent of application / use case)
- Explicit modeling of hardware configuration
- Efficient accounting of transition costs

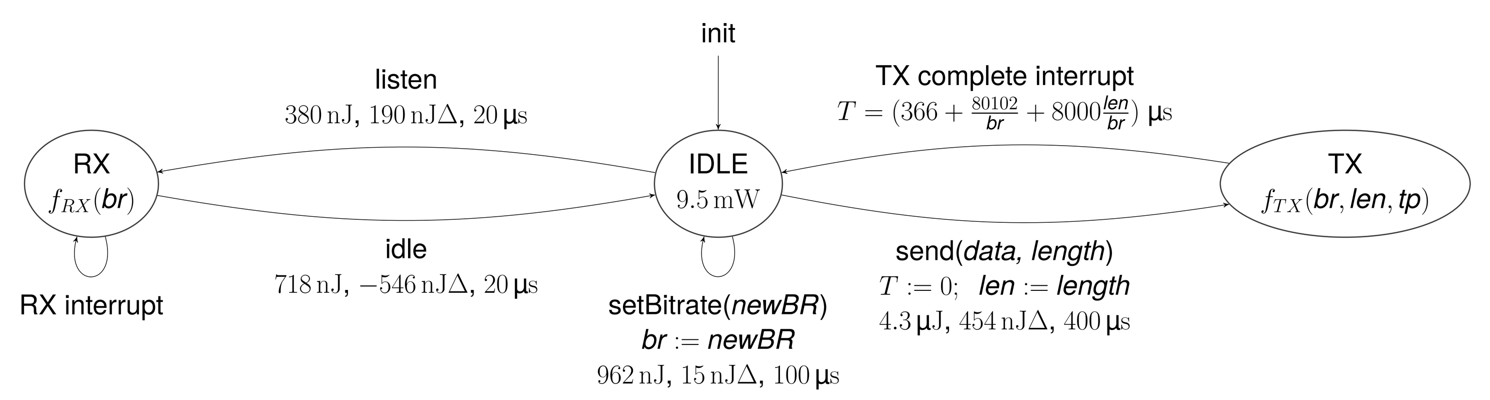


$\Rightarrow T_{TX}(br, len) = 366 + \frac{80102}{br} + 8000 \cdot \frac{len}{br}$

Model

Parameterized Priced Timed Automata (PTA):

- Parameters: hardware configuration, function arguments
- Price: transition energy, state power
- Time: transition duration and interrupt timers



Partial PTA energy model for a TI CC1200 radio module

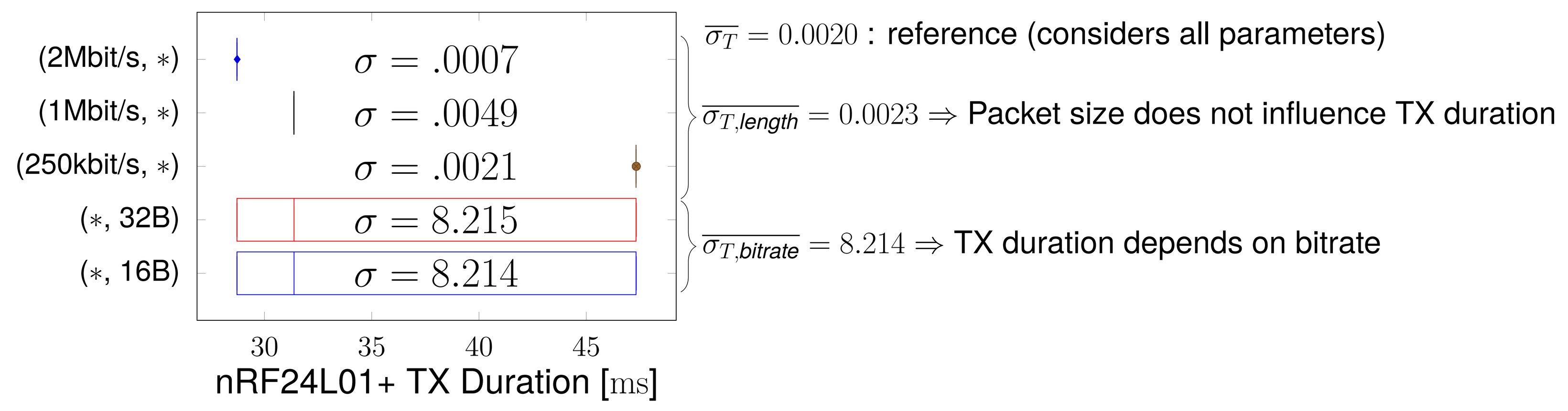
- PTA states $\widehat{=}$ hardware states; transitions $\widehat{=}$ driver functions
- One PTA per peripheral $\rightarrow$ independent of application software

Model Generation

Detecting parameter influence:

- Build look-up table model which ignores parameter i
- Compare with reference model (covering all parameters)
- Similar error $\rightarrow$ independent of i, otherwise dependent
- Data standard deviation $\approx$ model error for these models

$\rightarrow$ Heuristic: $> 50\,\%$ difference in standard deviation



Modeling parameter influence:

- Predefined set of simple function templates
- Determine best function for each parameter individually
  - Least squares regression on partitioned data
  - $\rightarrow$ Single variable parameter, all others constant
- Combine into a single function considering all parameters
  - Including interdependencies between parameters
  - Fitted using least squares regression on all data

Example: Mean RMSD of fitted functions for CC1200 TX duration

Template	$ax+b$	ax^2+b	$a\log(x)+b$	$\frac{a}{x}+b$
Bitrate	4984	5877	2636	**5**
Length	**4**	12125	20699	37685

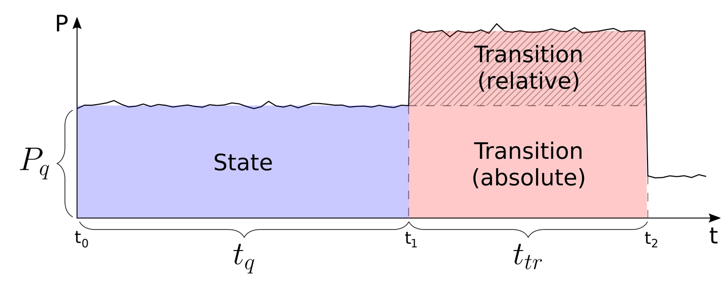
$\Rightarrow f_{bitrate}(br, len) = \frac{1}{br}$
$\Rightarrow f_{length}(br, len) = len$

$$\Rightarrow T_{TX}(br, len) = a_0 + \frac{a_1}{br} + a_2 \cdot len + a_3 \cdot \frac{len}{br}$$
$$= 366 + \frac{80102}{br} + 8000 \cdot \frac{len}{br}$$

Online Energy Accounting

- Without transition costs: one timestamp per state change
  - $E = P_{q_1} \cdot (t_2 - t_0) + P_{q_2} \cdot (t_4 - t_2) + \cdots$
- With transition costs: more accurate, but needs two timestamps
  - $E = P_{q_1} \cdot (t_1 - t_0) + E_{tr_1} + P_{q_2} \cdot (t_3 - t_2) + \cdots$
- Reason: transitions (driver functions) are not instantaneous
- But: Hardware state change usually is

$\rightarrow$ Only consider energy use which cannot be explained by the still active hardware state: *relative transition energy*



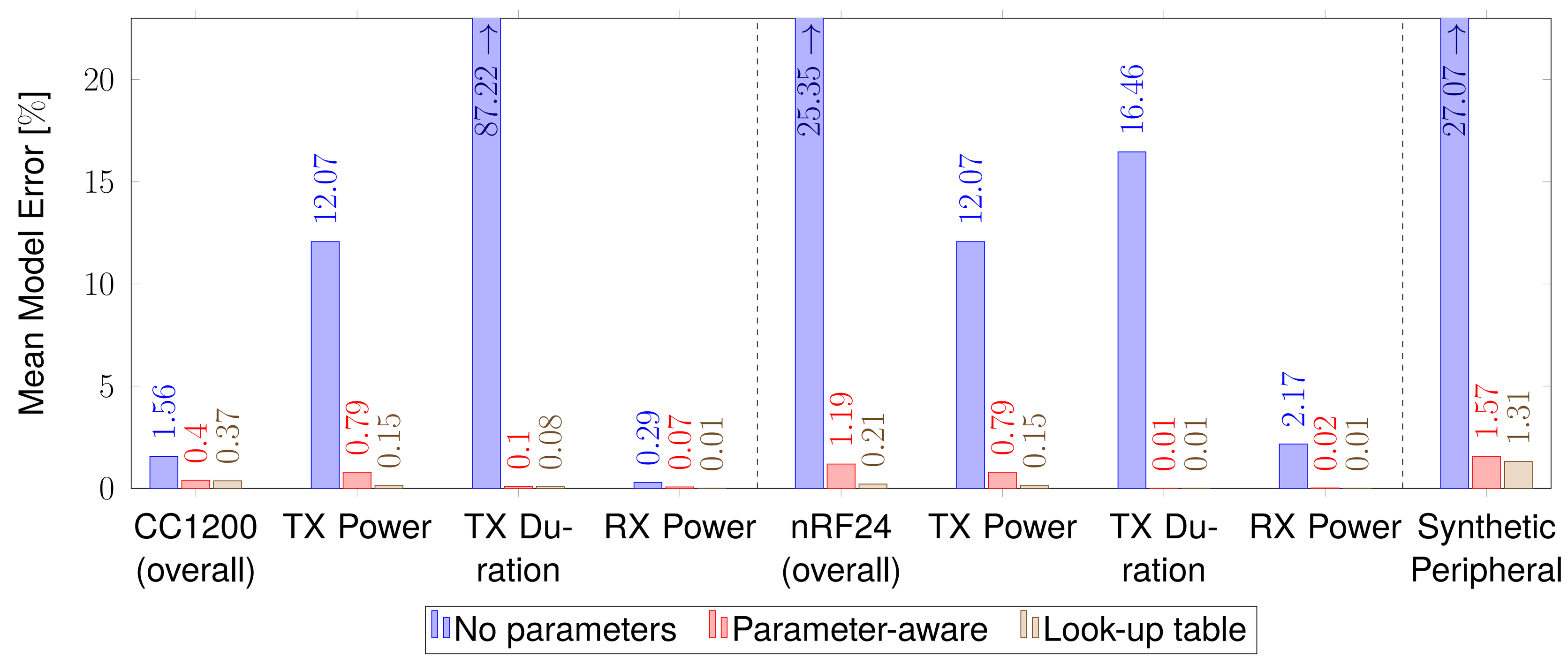
$$\Delta E_{tr} := E_{tr} - P_q \cdot t_{tr}$$
$$\Rightarrow P_q \cdot (t_1 - t_0) + E_{tr}$$
$$= P_q \cdot (t_2 - t_0) + \Delta E_{tr}$$

$\rightarrow$ Lower overhead: one timestamp per transition is sufficient

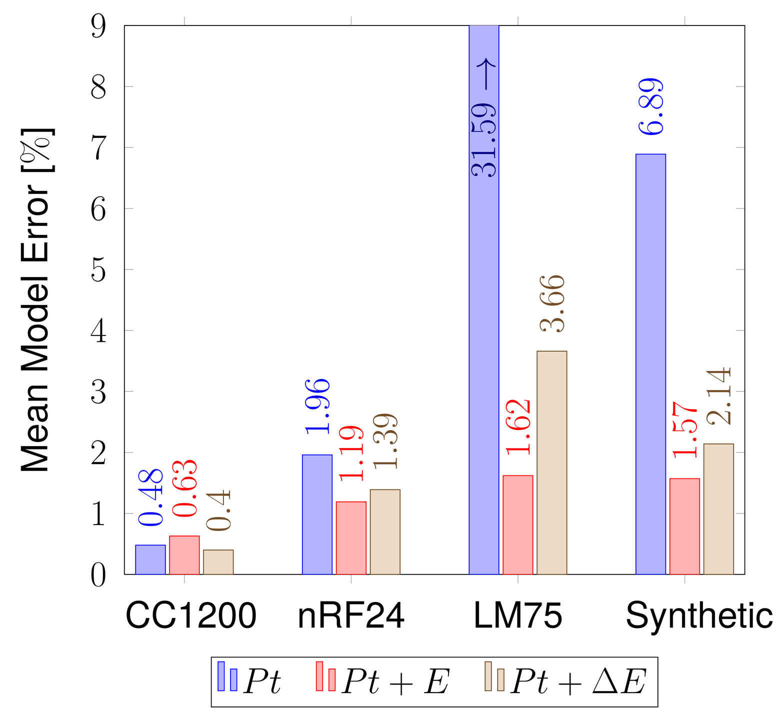
- $E = P_{q_1} \cdot (t_2 - t_0) + \Delta E_{tr_1} + P_{q_2} \cdot (t_4 - t_2) + \Delta E_{tr_2} + \cdots$

Preliminary Results

Evaluation of generated models for two SPI radio modules (TI CC1200, Nordic nRF24L01+), an I²C temperature sensor (LM75B) and a synthetic peripheral with configurable power consumption:



- Parameter detection improves model quality
  - Reliable for ≥ 4 distinct values per parameter
- Modeling transition energy also helps
  - Relative energy appears to be less accurate
- No overfitting due to limited function set



Future Work:

- Accomodate binary parameters / feature toggle functions
- Examine overhead $\leftrightarrow$ accuracy of online accounting variants