Composing Thermostatically Controlled Loads to Determine the Reliability against Blackouts

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The following equation describes the thermostat switching on and off:

$$\theta(t+1) = \underbrace{a\theta(t)}_{i)} + \underbrace{(1-a)(\theta_a - m(t)R \cdot P)}_{ii)} + \underbrace{g(t)}_{iii} [Callaway2009, p.8]$$
(1)



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Figure: Hysteresis

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Brief Problem Outline •0000000000 Practical Application •00 Practical Application

- A thermostat controls the air conditioner in a house.
- The set temperature θ_s is 20 °C, the ambient temperature θ_a is 32 °C.
- The hysteresis δ is 0.5 °C.



Figure: Hysteresis

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$$m_{i}(t_{n+1}) = \begin{cases} 0, & \theta(t) < \theta_{s} - \delta = \theta_{-} \\ 1, & \theta(t) > \theta_{s} + \delta = \theta_{+} \\ m(t) & \text{otherwise} \end{cases}$$
(2)

Basic	Parameters

Parameter	Meaning	Standard value	Unit
R	average thermal resistance	2	°C/ <i>kW</i>
С	average thermal capacitance	10	<i>kWh</i> / °C
Р	average energy transfer rate	14	kw
η	load efficiency	2.5	
θ_s	temperature set point	20	°C
δ	thermostat hysteresis	0.5	°C
θ_{a}	ambient temperature	32	°C

Table: Model parameters [Callaway2009]

Execution Trace

... with basic parameters and without noise:



Basic Parameters



Figure: Repetitive cycle of a switch remaining in a certain state

Conclusion

Manipulating the Parameters



- Binning: discretize continuous temperature domain
- noise: add noise function (third part of equation)

 \Rightarrow transition probabilities to *hop* from one bin to the next bin within one discrete time step.





2.5

3

3.5

4

4.5

2

19.5

0

0.5

1

1.5

hrs

5

Brief	Problem	Outline
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Conclusion

Binned Transition Abstraction



Figure: Binned Transition Abstraction, [Koch2009]

From BMP to DTMC

\downarrow from/to \rightarrow	1 on	2 on	1 off	2 off
1 on	p_1	1 – <i>p</i> ₁		
2 on		p_2	1 – <i>p</i> ₂	
1 off			p_3	$1 - p_{3}$
2 off	1 – <i>p</i> ₄			ρ_4

Table: Example symbolic DTMC for a surrogate housing \mathcal{D}_1

16 states, 64 transitions \rightarrow ten states, 36 transitions

Two Houses, two Bins

↓first quarter row		first quart	er column		Gest sugator serv			a vestar ash ma	
\downarrow from/to \rightarrow	(1on, 1on)	(1on, 2on)	(1on, 1off)	(1on, 2off)	tillst quarter row	(200, 100)	(2on 2on)	(2on 1off)	(200.20ff)
(1on, 1on)	D ² ;	$p_1 \cdot (1 - p_1)$			(1on 1on)	$p_1 \cdot (1 - p_1)$	$(1 - p_1)^2$	(200), 100/	(2011, 2011)
(1on 2on)		Di - Do	$n_{\rm e} \cdot (1 - n_{\rm p})$	1	(1on, 2on)	PI (* PI)	$(1 - p_1) \cdot p_2$	$(1 - p_1) \cdot (1 - p_2)$	
(1on 1off)		P1 P4	DL · DD	$n_{\rm e} \cdot (1 - n_{\rm p})$	(1on, 1off)			$(1 - p_1) \cdot p_3$	$(1 - p_1) \cdot (1 - p_3)$
(1on 2off)	$n_{11}(1-n_{1})$		P1 P3	P1 (1 P3)	(1on, 2off)	$(1 - p_1) \cdot (1 - p_1)$	()		$(1 - p_1) \cdot p_4$
(Torr, 2011)	P1 (1 P4)		and an and see a	P1 P4					
tsecond quarter ro	7W	second qu	larter column	1	isecond quarter row	N	third	quarter column	
\downarrow trom/to \rightarrow	(2on, 1on)	(2on, 2on)	(2on, 1ott)	(2on, 2ott)	\downarrow from/to \rightarrow	(1off, 1on)	(1off, 2o	n) (1off, 1off)	(1off, 2off)
(2on, 1on)	P2 · P1	$p_2 \cdot (1 - p_1)$			(2on, 1on)	$(1 - p_2)$	$(1 - p_2) \cdot (1$	- p1)	
(2on, 2on)		P2	$(1 - p_2) \cdot p_2$		(2on, 2on)		p2 · (1 -	p_2) $(1 - p_2)^2$	
(2on, 1off)			p2 · p3	$p_2 \cdot (1 - p_3)$	(2on, 1off)			$(1 - p_2) \cdot p_3$	$(1 - p_2) \cdot (1 - p_3)$
(2on, 2off)	$p_2 \cdot (1 - p_4)$			$P_2 \cdot P_4$	(2on, 2ott)	$(1 - p_2) \cdot (1 - p_2)$	P4)		$(1 - p_2) \cdot p_4$
I third quarter row		third auar	ten enlume						
		uniu quai	ter column						
\perp from/to \rightarrow	(1off, 1on)	(1off, 2on)	(1off, 1off)	(1off.2off)	Jthird quarter row	(And ten)	fourth o	quarter column	0.00
↓ from/to → /1off_1on>	(1off, 1on)	(1off, 2on)	(1off, 1off)	(1off, 2off)	↓third quarter row ↓ from/to → (1eff, 1ee)	(2off, 1on)	fourth o (2off, 2on	(2off, 1off)	(2off, 2off)
↓ from/to → (1off, 1on) (1off, 2on)	(1off, 1on) <i>p</i> ₃ · <i>p</i> ₁	(1 off, 2 on) $p_3 \cdot (1 - p_1)$	(1off, 1off)	(1off, 2off)	↓third quarter row ↓ from/to → (1off, 1on) (1off, 2on)	$\langle 2\text{off}, 1\text{on} \rangle$ $p_3 \cdot (1 - p_1)$	fourth c (2off, 2on (1 − p ₃) · (1 − (1 − p ₃)	quarter column (2off, 1off) - Pi) Pr (1 - Pr) (1 -	(2off, 2off)
↓ from/to → (1off, 1on) (1off, 2on) (1off, 1off)	(1off, 1on) <i>p</i> ₃ · <i>p</i> ₁	(10ff, 20n) $p_3 \cdot (1 - p_1)$ $p_3 \cdot p_2$	$\langle 1 \text{ off}, 1 \text{ off} \rangle$ $p_3 \cdot (1 - p_2)$	(1off, 2off)	↓third quarter row ↓ from/to → (1off, 1on) (1off, 2on) (1off, 1off)	(2off, 1on) $p_3 \cdot (1 - p_1)$	fourth (2011, 2011) (1 - p_3) · (1 - $(1 - p_3)$ · (1 - p_3) · (1 -	quarter column (2 off, 1 off) $(-p_1)$ p_2 $(1 - p_3) \cdot (1 - (1 - p_3)) \cdot p_3$	(2off, 2off) (1 - Pa) ²
↓ from/to → <1off, 1on> <1off, 2on> <1off, 1off>	(1off, 1on) <i>p</i> ₃ · <i>p</i> ₁	(10ff, 2on) $p_3 \cdot (1 - p_1)$ $p_3 \cdot p_2$	$\frac{\langle 1 \text{ off}, 1 \text{ off} \rangle}{p_3 \cdot (1 - p_2)}$ $\frac{p_3^2}{p_3^2}$	$\langle 1 \text{ off}, 2 \text{ off} \rangle$ $p_3 \cdot (1 - p_3)$	↓third quarter row ↓ from/to → (1off, 1on) (1off, 2on) (1off, 1off) (1off, 2off)	(2off, 1on) $p_3 \cdot (1 - p_1)$ $(1 - p_1) \cdot (1 - p_2)$	fourth c (2off, 2on $(1 - p_3) \cdot (1 - (1 - p_3)) \cdot (1 - (1 - p_$	quarter column (2 off, 1 off) (p_1) p_2 $(1 - p_3) \cdot (1 - (1 - p_3) \cdot p_2)$	(2off, 2off) (1 - P ₃) ² (1 - P ₃) - P ₄
↓ from/to → (1off, 1on) (1off, 2on) (1off, 1off) (1off, 2off)	$\langle 1 \text{off}, 1 \text{on} \rangle$ $p_3 \cdot p_1$ $p_3 \cdot (1 - p_4)$	$\langle 1 \text{off}, 2 \text{on} \rangle$ $p_3 \cdot (1 - p_1)$ $p_3 \cdot p_2$	$\frac{\langle 1 \text{ off, 1 off} \rangle}{p_3 \cdot (1 - p_2)}$ $\frac{p_3^2}{p_3^2}$	(1 off, 2 off) $p_3 \cdot (1 - p_3)$ $p_3 \cdot p_4$	↓ third quarter row ↓ from/to → (1off, 1on) (1off, 2on) (1off, 1off) (1off, 2off)	(2off, 1on) $p_3 \cdot (1 - p_1)$ $(1 - p_3) \cdot (1 - p_3)$	fourth c (2off, 2on $(1 - p_3) \cdot (1 - (1 - (1 - p_3) \cdot (1 - (1 - (1 - (1 - (1 - (1 - (1 - (1$	$\begin{array}{c c} \begin{array}{c} \text{uarter column} \\ \hline & (20\text{ff}, 10\text{ff}) \\ \hline & p_1 \\ p_2 \\ \hline & (1 - p_3) \cdot (1 - (1 - p_3) \cdot p_3) \\ \hline \end{array}$	(2 off, 2 off) $(1 - p_3)^2$ $(1 - p_3) \cdot p_4$
↓ from/to →	$\begin{array}{c} \langle 1 \text{off}, 1 \text{on} \rangle \\ p_3 \cdot p_1 \\ \hline \\ p_3 \cdot (1 - p_4) \end{array}$	fourth quart	$\langle 1 \text{ off}, 1 \text{ off} \rangle$ $p_3 \cdot (1 - p_2)$ p_3^2	$\langle 1 \text{ off}, 2 \text{ off} \rangle$ $p_3 \cdot (1 - p_3)$ $p_3 \cdot p_4$	\$third quarter row \$from/to → {10ff, 10n) {10ff, 20n) {10ff, 20n} {10ff, 20ff} {10ff, 20ff} {10ff, 20ff}	(2 off, 1on) $p_3 \cdot (1 - p_1)$ $(1 - p_3) \cdot (1 - p_1)$ row	fourth c (2off, 2on) (1 - p ₃) · (1 (1 - p ₃) ·) (4)	quarter column (2off, 1off) P_2 $(1 - P_3) \cdot (1 - (1 - P_3) \cdot P_2)$ quarter column	(2off, 2off) (1 − p ₃) ² (1 − p ₃) · p ₄
↓ from/to → (1off, 1on) (1off, 2on) (1off, 2off) ↓fourth quarter row	$\langle 1 \text{ off}, 1 \text{ on} \rangle$ $p_3 \cdot p_1$ $p_3 \cdot (1 - p_4)$ $\langle 1 \text{ on}, 1 \text{ on} \rangle$	(1 off, 2 on) $p_3 \cdot (1 - p_1)$ $p_3 \cdot p_2$ fourth quart	Provident condition $\langle 1 \text{ off}, 1 \text{ off} \rangle$ $p_3 \cdot (1 - p_2)$ p_3^2 er column (1 on 1 off)	$\langle 1 \text{ off}, 2 \text{ off} \rangle$ $p_3 \cdot (1 - p_3)$ $p_3 \cdot p_4$ $\langle 1 \text{ on } 2 \text{ off} \rangle$	↓third quarter row ↓from/to → (1off, 1on) (1off, 2on) (1off, 2on) (1off, 2off) ↓fourth quarter ↓ from/to →	(2 off, 1on) $p_3 \cdot (1 - p_1)$ $(1 - p_5) \cdot (1 - p_2)$ row (2 off, 1on)	fourth c (2off, 2on (1 − p ₃) · (1 − (1 − p ₃) · (1 (1 − p ₃) · (1 (1 − p ₃) · (1 (2 − p ₃) · (1)) (2 − p ₃) · (1))	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	(2off, 2off) p_2) $(1 - p_3)^2$ $(1 - p_3) \cdot p_4$ (2off, 2off)
↓ from/to → (1off, 1on) (1off, 2on) (1off, 2off) (1off, 2off) ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓	$\langle 1 \text{ off, } 1 \text{ on} \rangle$ $p_3 \cdot p_1$ $p_3 \cdot (1 - p_4)$ $\langle (1 - p_1) \cdot p_2 \rangle (1 - p_4)$	fourth qual (10ff, 2on) $p_3 \cdot (1 - p_1)$ $p_3 \cdot p_2$ fourth quart 10n, 2on)	$\begin{array}{c} (1 \text{ off, 1 off, }) \\ \hline p_3 \cdot (1 - p_2) \\ \hline p_3^2 \\ \end{array}$	$\langle 1 \text{off}, 2 \text{off} \rangle$ $p_3 \cdot (1 - p_3)$ $p_3 \cdot p_4$ (1 on, 2 off)	↓third quarter row ↓ from/to → (1off, 1on) (1off, 2on) (1off, 2off) ↓ fourth quarter ↓ from/to → (2off, 1on)	$\langle 2 \text{off}, 1 \text{on} \rangle$ $p_5 \cdot (1 - p_1)$ $(1 - p_5) \cdot (1 - p$ row $\langle 2 \text{off}, 1 \text{c}$ $p_6 \cdot p$	fourth c (2off, 2on (1 - p_3) · (1 - (1 - p_3) · (1 - (1 - p_3) · (1 - (1 - p_3) · (1 - (2 off, 2on (1 - p_4 · (1 -	$\begin{array}{c c} \text{quarter column} \\ \hline & (2\text{off, 1off}) \\ \hline p_2 & (1 - p_3) \cdot (1 - (1 - p_3) \cdot p_2) \\ \hline & (1 - p_3) \cdot p_2 \\ \hline & (2\text{off, 1off}) \\ \hline p_1 \\ \end{array}$	(2off, 2off) P_{R} $(1 - P_{3})^{2}$ $(1 - P_{3}) \cdot P_{4}$ (2off, 2off)
↓ from/to → (10ff, 1on) (10ff, 2on) (10ff, 2off) ↓ from/to → (2off, 1on) (2off, 1on)	$\begin{array}{c c} \langle 1 \text{off}, 1 \text{on} \rangle \\ \hline p_3 \cdot p_1 \\ \hline p_3 \cdot (1 - p_4) \\ \hline (1 \text{on}, 1 \text{on}) & \langle 1 - (1 - p_4) \rangle \\ \hline (1 - p_4) \cdot p_1 & (1 - (1 - (1 - p_4))) \\ \hline (1 - p_4) \cdot p_1 & (1 - (1 - (1 - p_4))) \\ \hline (1 - p_4) \cdot p_1 & (1 - (1 - (1 - p_4))) \\ \hline (1 - p_4) \cdot p_1 & (1 - (1 - (1 - (1 - p_4)))) \\ \hline (1 - p_4) \cdot p_1 & (1 - (1 - (1 - (1 - (1 - (1 - (1 - ($	$\begin{array}{c} \text{fund quart} \\ (1 \text{ off}, 2 \text{ on}) \\ p_3 \cdot (1 - p_1) \\ p_3 \cdot p_2 \\ \hline \\ \text{fourth quart} \\ 1 \text{ on}, 2 \text{ on}) \\ p_4 \cdot (1 - p_1) \\ p_4 \cdot (1 - p_1) \\ p_4 = p_4 \cdot p_2 (1 \ \text{ on}) \\ \end{array}$	$\begin{array}{c} (1 \text{ off, 1 off}) \\ \hline p_3 \cdot (1 - p_2) \\ p_3^2 \\ er \ column \\ (1 \text{ on, 1 off}) \\ \hline - p_4) \cdot (1 - p_2) \end{array}$	$\langle 1 \text{ off}, 2 \text{ off} \rangle$ $p_3 \cdot (1 - p_3)$ $p_3 \cdot p_4$ $\langle 1 \text{ on}, 2 \text{ off} \rangle$	↓third quarter row ↓ from/to → (1off, 1on) (1off, 2on) (1off, 2on) (1off, 2off) ↓fourth quarter ↓ from/to → (2off, 1on) (2off, 2on)	$(2off, 1on) p_3 \cdot (1 - p_1) (1 - p_3) \cdot (1 - p_1) (1 - p_3) \cdot (1 - p_1) (2off, 10 p_4 \cdot p_1) $	fourth c $(2off, 2on (1 - p_3) \cdot (1 - (1 - (1 - (1 - (1 - (1 - (1 - (1$	$\begin{array}{c c} \text{quarter column} \\ \hline & (2off, 1off) \\ -p_1) \\ p_2 \\ (1-p_3) \cdot (1- (1-p_3) \cdot p_1) \\ quarter column \\ n) \\ (2off, 1off) \\ p_1) \\ \hline \\ p_0 \\ p_1 \\ \end{array}$	$\langle 2 \text{off}, 2 \text{off} \rangle$ p_2 $(1 - p_3)^2$ $(1 - p_3) \cdot p_4$ $\langle 2 \text{off}, 2 \text{off} \rangle$
↓ from/to → ↓ form/to → (1off, 1on) ↓ form/to → ↓ from/to → (2off, 1on) ↓ from/to → (2off, 1on) (2off, 1off)	$\begin{array}{c c} \langle 1 \text{off}, 1 \text{on} \rangle \\ \hline p_3 \cdot p_1 \\ \hline p_3 \cdot (1 - p_4) \\ \hline \langle 1 \text{on}, 1 \text{on} \rangle & \langle 1 - p_4 \rangle \cdot p_1 \\ \hline (1 - p_4) \cdot p_1 & (1 - q_1) \\ \hline \end{pmatrix}$	$\begin{array}{c c} \text{fund quart} \\ (1 \text{ off}, 2 \text{ on}) \\ \hline p_3 \cdot (1 - p_1) \\ \hline p_3 \cdot p_2 \\ \hline \text{fourth quart} \\ 1 \text{ on}, 2 \text{ on}) \\ \hline p_4 \cdot (1 - p_1) \\ \hline - p_4 \cdot p_2 \end{array} (1$	$\begin{array}{c} (1 \text{ off, 1 off}) \\ \hline p_3 \cdot (1 - p_2) \\ p_3^2 \\ \hline p_3^2 \\ er \ column \\ (1 \text{ on, 1 off}) \\ \hline -p_4) \cdot (1 - p_2) \\ (1 - p_4) \cdot p_3 \end{array}$	$(1 \text{ off}, 2 \text{ off})$ $p_3 \cdot (1 - p_3)$ $p_3 \cdot p_4$ $(1 \text{ on}, 2 \text{ off})$ $(1 - p_4) \cdot (1 - p_3)$	third quarter row ↓fromNo → {off, Ion) {off, Ion) {off, Ion) {off, Ion) {off, Ion) {off, Ion) {off, 2on) {off, 2on) {off, 2on) {off, 2on) {off, 2on) {off, 2on) {off, 2on} {off, 1on) {off, 1on {off, 1on } } {off, 1on } {off, 1on } } {off, 1on } } {off, 1on } } {off, 1on } } }	(2off, 1on) $p_3 \cdot (1 - p_1)$ (1 - p_3) · (1 - p_1 row (2off, 1c $p_4 \cdot p_1$	$\begin{array}{c c} \text{fourth } c \\ (2off, 2on \\ (1 - p_3) \cdot (1 - \\ (1 - p_3) \cdot (1 - \\ (1 - p_3) \cdot) + \\ (1 - p_3) \cdot (1 - \\ (1 - p_3) \cdot) + \\ (1 - p_3) \cdot (1 - \\ p_4 \cdot (1 - \\ p_4 \cdot p_4 \cdot p_4 - p_4 \cdot p_4 + $	$\begin{array}{c} \begin{array}{c} \begin{array}{c} \text{uurter column} \\ \hline & (2off, 1off) \\ p_2 \end{array} & (1 - p_3) \cdot (1 - (1 - p_3) \cdot p_3) \\ \hline \end{array} \\ \begin{array}{c} \begin{array}{c} \text{quarter column} \\ \text{quarter column} \\ \text{quarter column} \\ \hline \end{array} & (2off, 1off) \\ \hline \end{array} \\ \begin{array}{c} \begin{array}{c} p_4 \cdot (1 - p_2) \\ p_4 \cdot (2 - p_3) \end{array} \\ \end{array} \end{array}$	$\langle 2off, 2off \rangle$ p_2 $(1 - p_3)^2$ $(1 - p_3) \cdot p_4$ $\langle 2off, 2off \rangle$ $p_4 \cdot (1 - p_3)$

Table: Example TCL DTMC composition D_2 , 16 states, 64 transitions

Brief P	roblem Outl		Practical Application	
		-		

Conclusion

Wireless Sensor Network



Figure: Lumping scheme showing which states are bisimilar

, from/to →	(1on, 1on)	(1on,2on)	(1on,1off	(1 on, 2	off)	(2on, 2on)	(20n,10ff)	(2 or	1,2 off)
(1on, 1on)	P1	$2 \cdot p_1 \cdot (1 - p_1)$)			$(1 - p_1)^2$				
(1 on, 2 on)		$p_1 \cdot p_2$	$p_1 \cdot (1 - p_1)$	b)		$(1 - p_1) \cdot p_2$	$(1 - p_1) \cdot (1 - p_2)$	$-\rho_2)$		
(1on, 1off)			$p_1 \cdot p_3$	p1 · (1 -	(ρ_3)		$(1 - p_1) \cdot p_1$	23 (1	$(-p_1)$	$(1 - p_3)$
(10n, 2 off)	$p_1 \cdot (1 - p_4)$	$((1 - p_1) \cdot (1 - p_2))$	24)	p1 · p	4				(1 –	p1) · p4
; from/to \rightarrow	(1on, 2on)	(1on, 1off)	(1on,2off)	2on, 2on)	(2)	on,1off)	(2on,2off)	(1off,	1off)	(1off, 2off)
(2on, 2on)				P2	2 · (1	- P2) · P2		(1 -	$P_2)^2$	
(2 on, 1 off)		P2 · P3 P	$-2 \cdot (1 - p_3)$			[1	$-p_2$) · (1 - p_3	1 - p	2) · P3	
(2on, 2off)	$p_1 \cdot (1 - p_4)$	$1 - p_1 \cdot (1 - p_4)$					P2 · P4		<u> </u>	1 – p₂) · p
↓ from/to	\rightarrow (1on, 1	lon) (1on, 1o	(1c	on, 2off)		(1off, 1of	f) (10ff, 2	off〉	(20	ff, 2off)
(1off, 1of	fγ					p_{3}^{2}	2 · (1 – p	$_3) \cdot p_3$	(1	$(-p_3)^2$
(1off, 2of	f)	p ₃ · (1 −	$p_4)(1 - p_3)$	3) · (1 –	p4)		p3 · p	24	(1 –	$p_3) \cdot p_4$
(2off, 2of	f) (1 – p	0 ₄) ²	2 · (1	- p ₄) ·	p ₄					p_{4}^{2}

Table: Lumped DTMC \mathcal{D}'_2 , ten states, 36 transitions

State Space Explosion with and without Lumping





(a) Dampening the state space explosion in the first ten steps



(b) Dampening the state space explosion in the first 100 steps

number of housings in on mode (origin)



Problem	Outline



Figure: Time consumption to compute 1000 housings TCL power grid



Figure: Determining the risk to crash



Figure: Limiting window reliability over 100 time steps



Figure: Limiting window reliability over 10,000 time steps

- scope: computing reliability of homogeneous TCLs against blackout
- **method**: parallel composition
- ▶ focus: exploit leverage, i.e. mutual independence of TCL
- result: compared to hierarchical/semi-hierarchical scenarios, composing mutually independent TCL is trivial

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Questions?