Optimal Selection of Voltage Regulator Modules in a Power Delivery Network

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Outline

- Introduction
- Voltage Regulator Modules (VRM’s)
- Selection of VRM’s in a PDN
  - VRM Tree Optimization Algorithm
  - Practical Issues
- Simulation Results
- Conclusions

Introduction

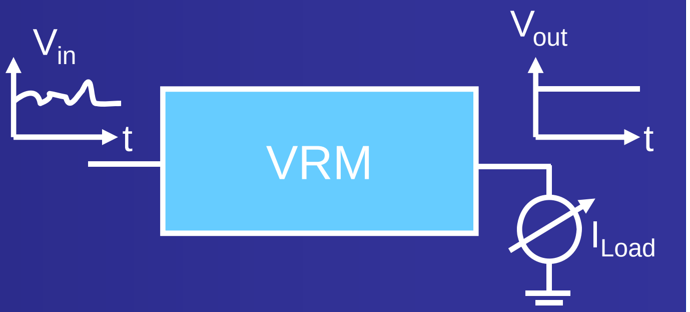
- Power delivery network (PDN) is a critical design component
- PDN design comprises of three steps:
  - Establishing a PDN target impedance

$$Z_{tar} = \frac{\Delta V_{dd}}{\Delta I} \quad [illegible]$$

  - Designing a proper system-level decoupling network
    - Needed to achieve target impedance over a broad frequency band
  - Selecting the right voltage regulator modules (VRM’s)
    - VRM provides constant DC output voltage

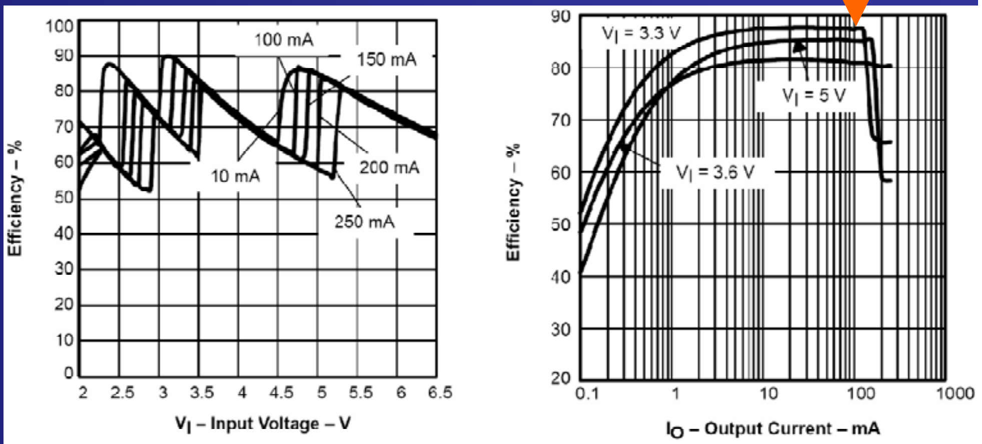
Voltage Regulator Modules (VRM's)

- VRM tasks
  - Voltage regulation
    - Achieved by a feedback loop
  - DC-DC conversion
    - Step-down (Buck)
    - Step-up (Boost)
    - Buck-Boost

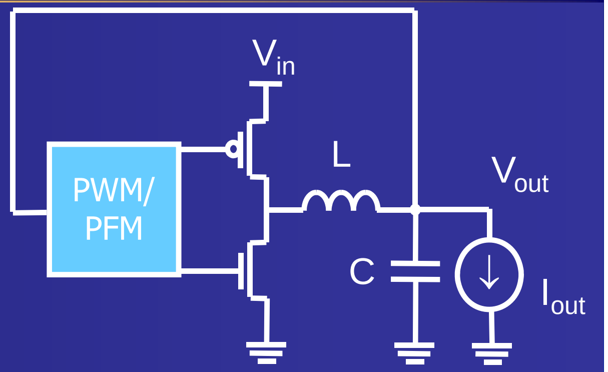


- Power efficiency

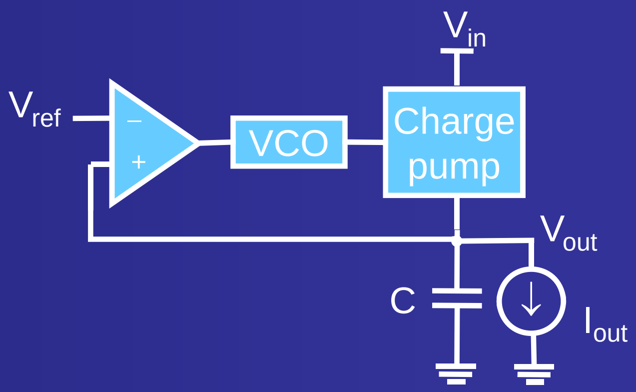
[illegible]



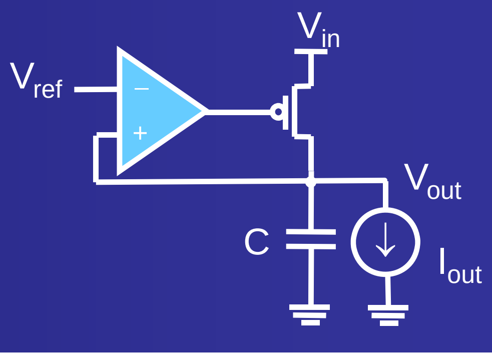
Different Types of VRM's



- Inductor-based VRM's
  - Inductors are energy storage
    - – Requires off-chip inductor



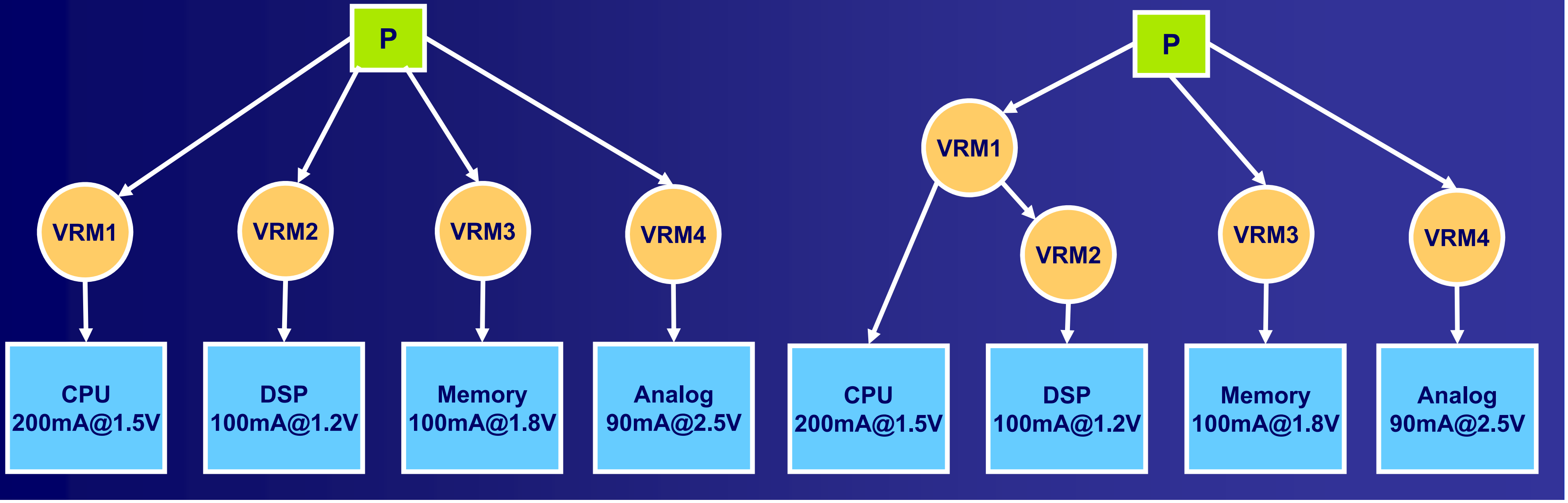
- Charge-pump VRM's
  - Capacitors are energy storage
    - – Suitable for handheld devices



- Linear VRM's
  - Require few or no reactive components
    - – More integrable compared to switching VRM's
  - Efficiency limited by V_{out}/V_{in}
    - – Most efficient form: low-dropout regulator (LDO)

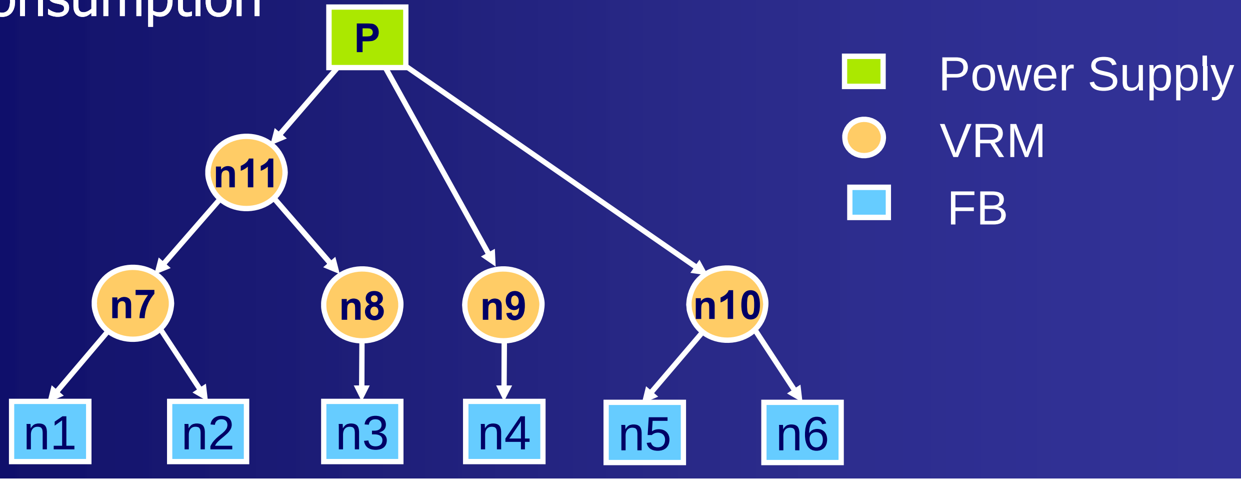
Voltage Regulator Module Tree

- Multiple voltage domains on SoC
  - Different functional blocks (FB's) have different voltage and current demand
- A topology of VRM's needed to deliver power
  - Typically a star topology of VRM is used
  - A tree topology of VRM may be more power efficient



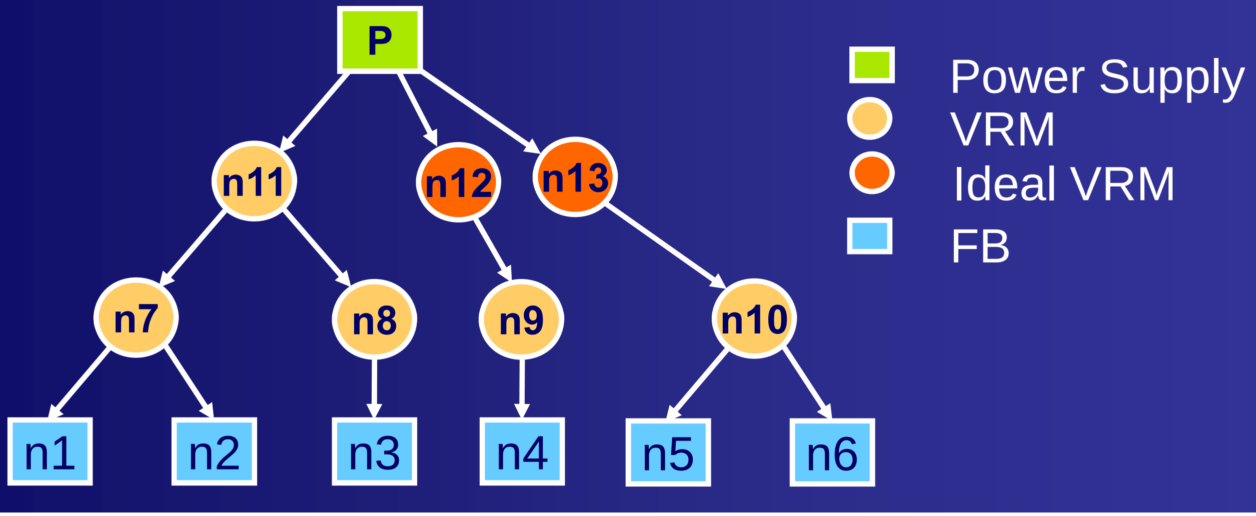
VRM Tree Optimization for Min Power Loss

- VRM Tree Optimization (RMTO) Problem:
  - Given is:
    - A library $\mathcal{R}$ of VRM's; $\forall r \in \mathcal{R}$:
      - V_{out}, min and max V_{in}, max I_{out}
      - efficiency $\eta_r = f(V_{in}, I_{out})$
    - A set $\mathcal{L}$ loads; $\forall l \in \mathcal{L}$: (V_l, I_l)
    - A power source P, with the nominal voltage of V_P
  - Objective is
    - Build a VRM tree b/w P and loads to minimize the power consumption



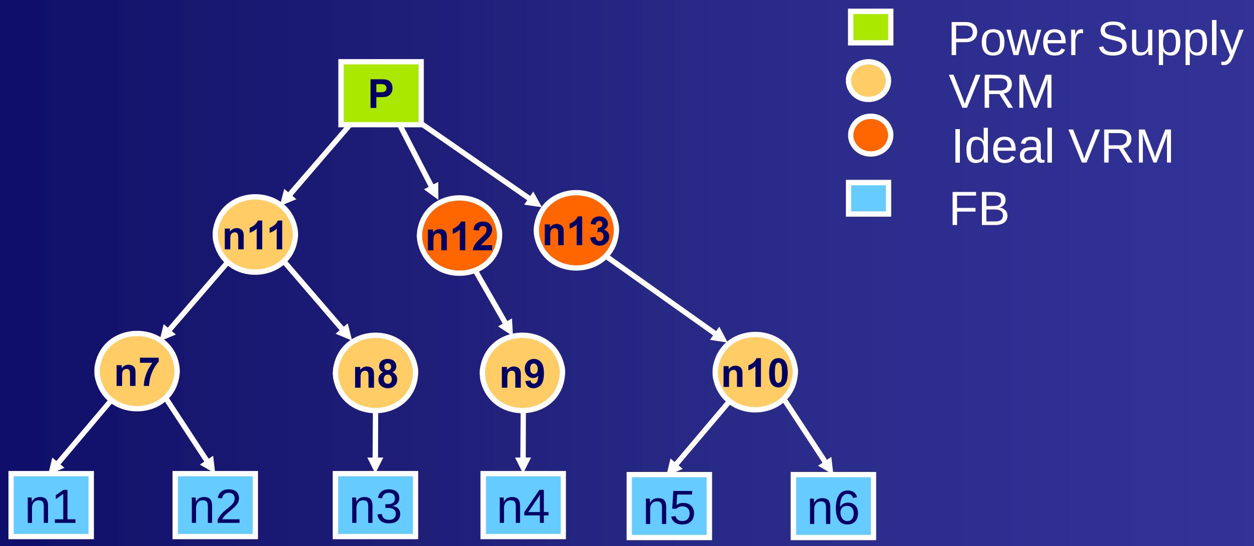
RMTO Problem

- RMTO problem definition does not put any constraint on VRM tree depth
- In practice such a constraint is useful to manage cost
  - Up to two level regulator in VRM tree
- To make a balanced-height VRM tree
  - Insert ideal VRM’s
- Assumption: Each VRM’s produce a single V_{out}



RMTO-FM Problem

- Monotone input current property (MICP) of a VRM
  - I_{in} is a monotone increasing function of I_{out} independent of V_{in}
- If tree topology is fixed and MICP holds, RMTO-FM is solved using dynamic programming
  - Performing BFS starting from leaves

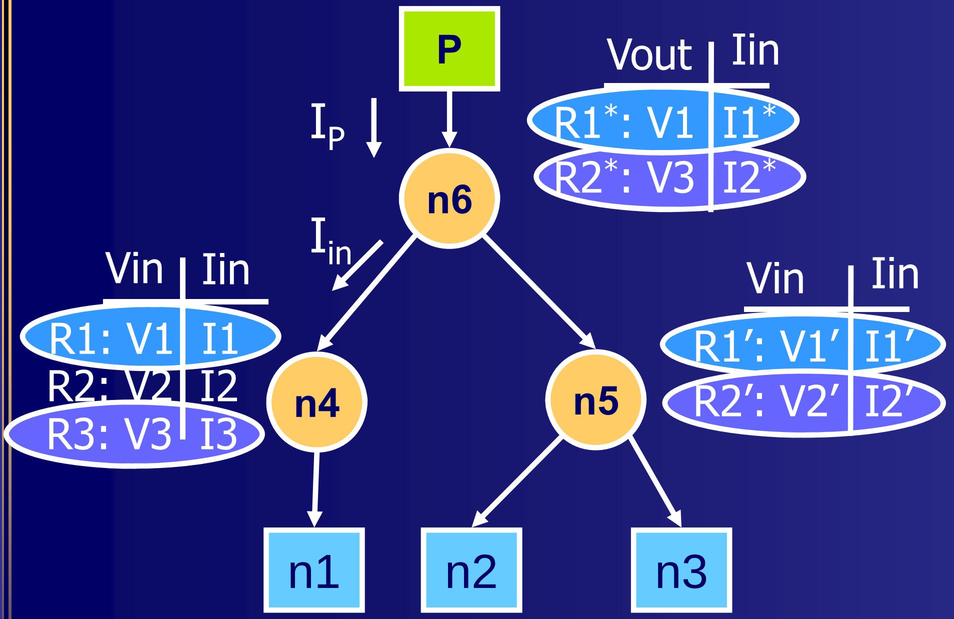


RMTO-FM Algorithm

Candidate VRM's for n4: {R1, R2, R3, R4}
$\mathcal{U}$: Set of all output voltages of VRM's

$Eff(V_{in})$

$I_{in} = \frac{V_{out}}{V_{in} Eff(V_{in})}$



RMTO-FM Algorithm

```
For each second level node $n_2$
  $\exists v \in \mathcal{U}$
      Find  VRM which minimizes $I_{in}(n_2)$
For each first level node $n_1$
  $\exists v \in \cap \mathcal{V}_m$: m$\in$Fanout(n)
      Find VRM which minimizes $I_{in}(n_1)$
Return best VRM assignment
```

$\mathcal{V}_n$: Set of all candidate V_{in} for node *n*

RMTO-VM Algorithm

- If tree topology is varied and MICP holds, RMTO-VM is solved by enumerating all *feasible* trees

```
RMTO-VM ($\mathcal{R}$, $\mathcal{L}$, $V_P$)
Begin
For each $T \in \mathcal{T}_2(n)$
    If $T$ is feasible
        RMTO-FM ($\mathcal{R}$, $\mathcal{L}$, $T$, $V_P$)
    End
End
Return best RMTO-FM ($\mathcal{R}$, $\mathcal{L}$, $T$, $V_P$)
End
```

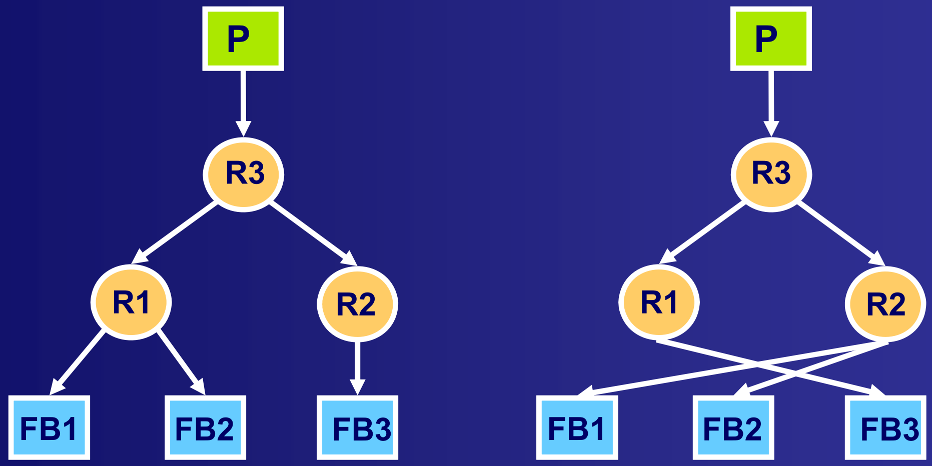
$\mathcal{R}$: set of VRM's

$\mathcal{L}$: set of loads

$\mathcal{T}_2(n)$: All trees with exactly two internal nodes and n leaves

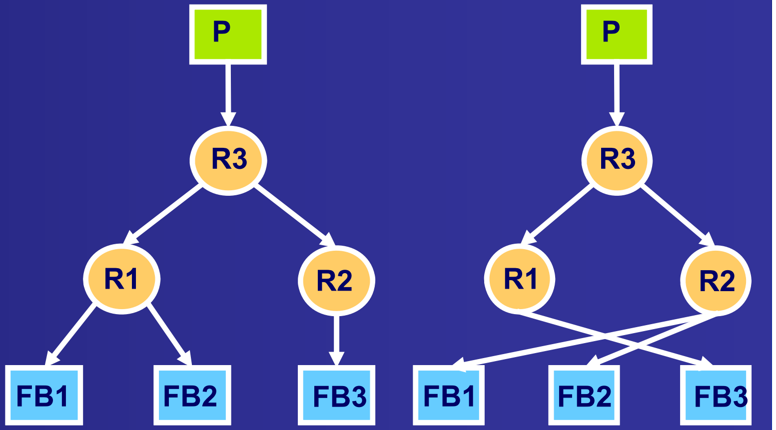
Tree Generation

- A VRM tree topology is *feasible* if
  - Its depth is exactly four
  - Leaf nodes under any second-level internal node have same voltage assignments.
- Number of feasible trees with *n* leaves is quite large
- In RMTO problem, many feasible trees are isomorphic



Tree Generation (cont'd)

- Two VRM trees are *inter-isomorphic* if they become equal by a change of labeling in intermediate vertices



- Number of non-inter-isomorphic trees with exactly *n* leaf nodes and two intermediate nodes:

$$|\mathcal{T}_2(n)| = \sum$$ [illegible]

$\left\{ {n \atop k} \right\}$: Stirling number of second kind

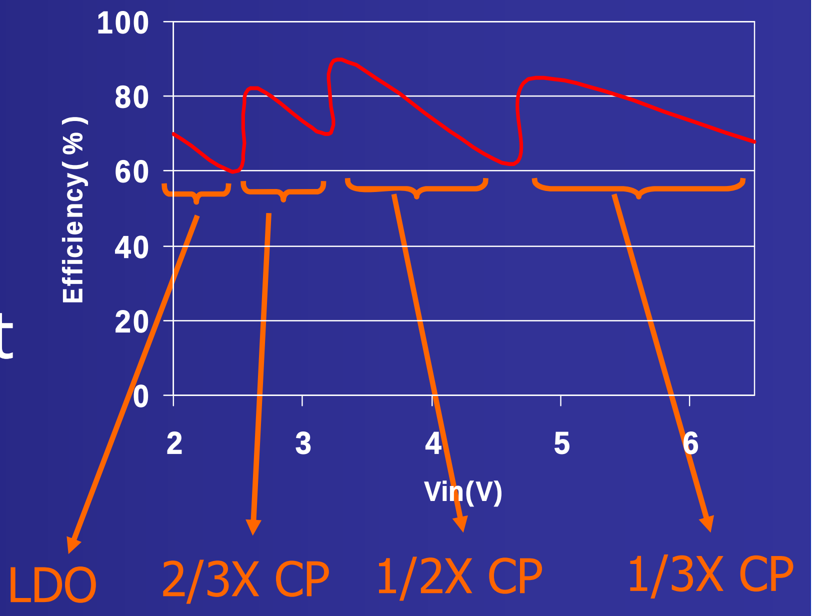
n	1	2	3	4	5
$\lvert\mathcal{T}_2(n)\rvert$	1	3	12	60	358

- Set of non-inter-isomorphic trees generated using *restricted growth strings* (RGS)

Practical Issue I: Effect of Non-Monotone Input Current

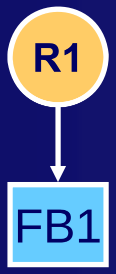
- MICP holds if VRM has a single mode

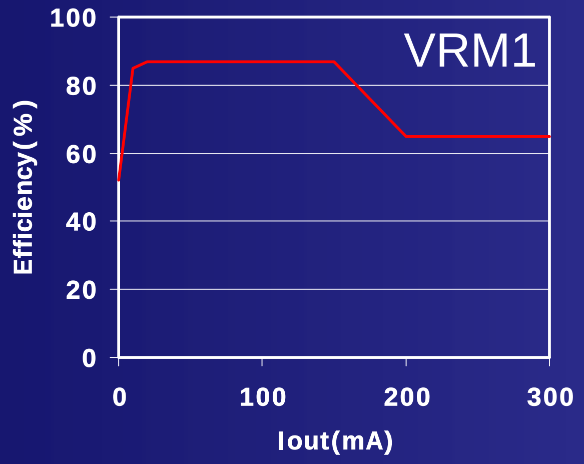
- Some VRM's operate at different modes depending on applied V_{in}
  - Non-monotone input current vs. output current behavior
  - Principle of dynamic programming is broken
    - RMTO-FN/VN require exhaustive search
  - Change in RMTO-VM
    - Lookup tables in level-2 nodes become 2-D

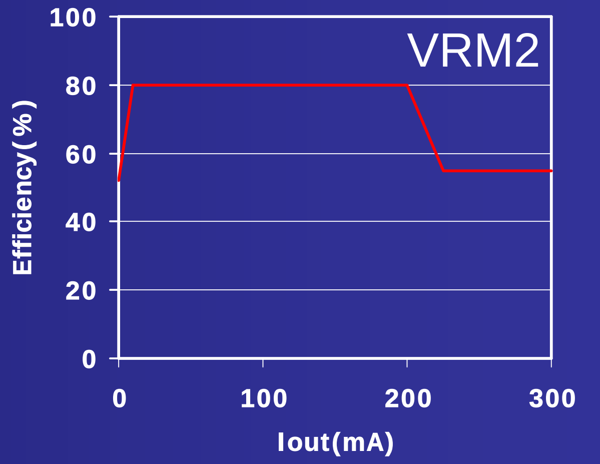


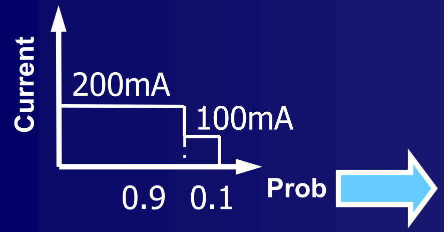
Practical Issue II:
Effect of Current Profile of Loads

- Current profiles play a key role in optimal VRM selection
- Motivational example:
  - VRM1 and VRM2 are candidate VRM's for FB1





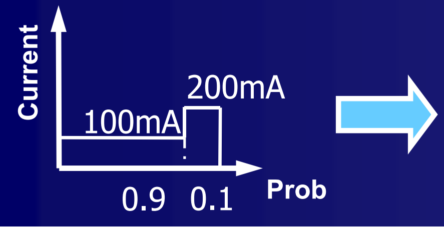




[illegible]

$\bar{\eta}_{VRM1} = 0.8$[illegible]

VRM2 is more power efficient



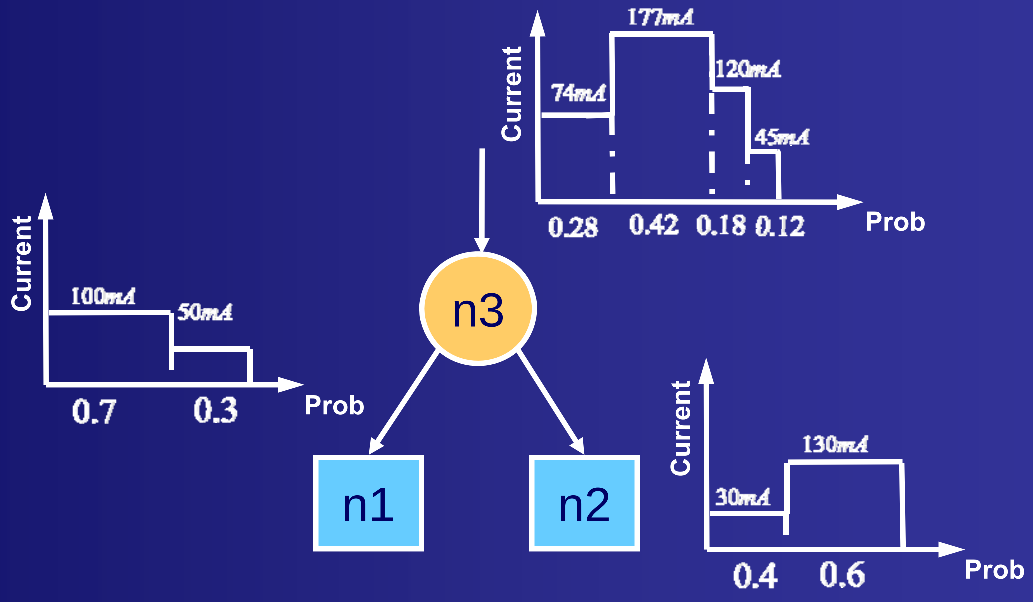
[illegible]

$\bar{\eta}_{VRM1} = 0.8$[illegible]

VRM1 is more power efficient

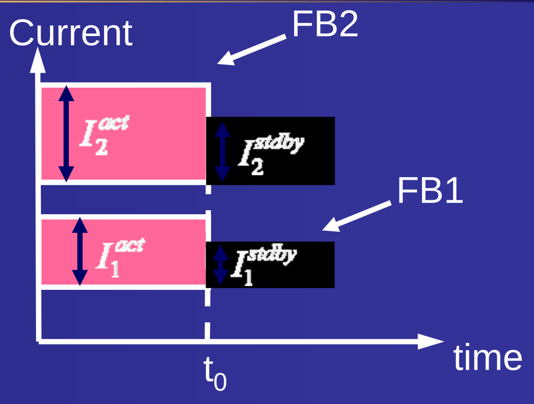
Practical Issue II:
Effect of Current Profile of Loads (cont'd)

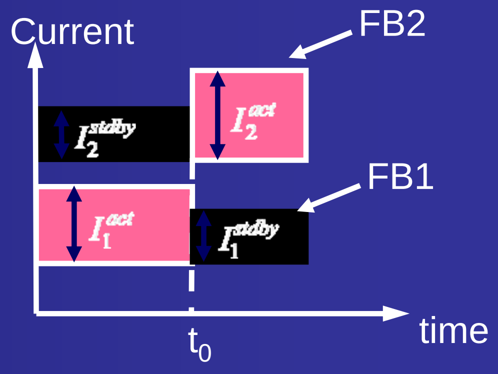
- Change in RMTO-FM algorithm to account for effect of current profile:
  - Efficiency and I_{in} of a candidate VRM become PWL function
- Assumption: profiles of different FB's are independent of one another



Practical Issue III: Effect of Current Profile Correlations

- Correlation b/w load profiles could be used to design more efficient VRM tree
- Motivational example:
  - – Positively correlated FB's
    - Parallel processor cores
  - – Negatively correlated FB's
    - Activity migration
- Efficiency and I_{in} of a candidate VRM become PWL function





Experimental Setup

- Proposed algorithms implemented in C++
- A set of 30 commercial VRM's from Texas Instruments and National Semiconductors used as library of VRM's.
- Results of RMTO-VM compared with results of optimal VRM assignment in a star topology (RMTO-SM)

Benchmark Characteristics

Circuit	V_P	N	I_{min}	I_{max}	V_{min}	V_{max}
TB1	2.5	6	50m	100m	1.1	1.8
TB2	2.5	7	50m	200m	1.3	1.8
TB3	2.5	5	60m	200m	1.3	3.0
TB4	2.5	8	50m	200m	1.3	3.3
TB5	3.3	6	30m	100m	1.2	1.8
TB6	3.3	10	50m	300m	1.1	2.7
TB7	3.3	12	30m	350m	1.1	3.0
TB8	3.3	8	50m	200m	1.3	3.3

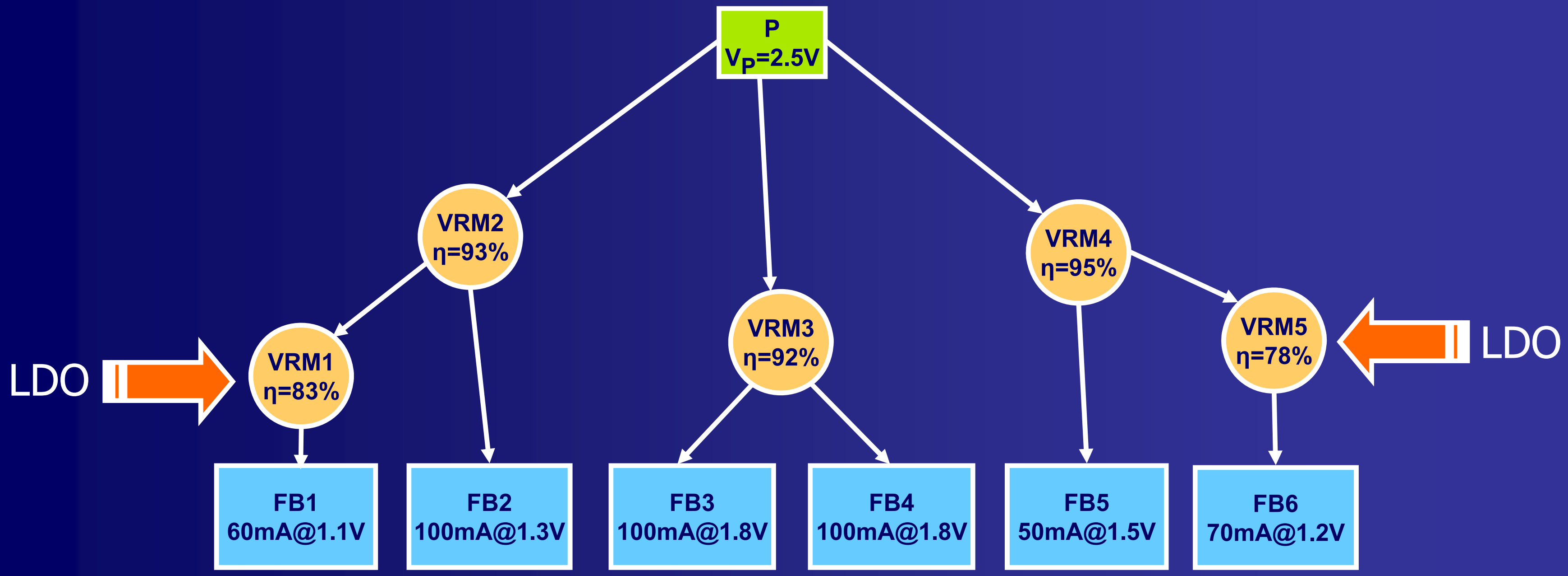
Experimental Results

Circuit	VRM Tree Power Loss (mW)		VRM Tree Power Dissipation Reduction (%)
	RMTO-SM	RMTO-VM	
TB1	114	89	21.9
TB2	72	55	23.6
TB3	110	94	14.5
TB4	381	345	9.4
TB5	144	123	14.6
TB6	242	190	21.5
TB7	621	545	12.3
TB8	451	370	17.9

- RMTO-VM reduces power dissipation in VRM tree by an average of 17.9%

Experimental Results (cont'd)

- Optimal VRM Tree for TB1



- 21.9% power reduction in VRM tree

Conclusion

- Using a multi-level VRM tree and optimally selecting VRM is beneficial for power reduction in PDN
- Modeled VRM tree optimization problem as a dynamic program and efficiently solved it
- On average about 18% power reduction in the VRM tree can be achieved by using a VRM tree topology

Thank You!