How to make early thermal assessments and decisions using a simple resistor network

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Managing heat dissipation is one of the biggest challenges when designing electronic components and systems today. You can run simulations and measure full systems with high accuracy, but that can be time-consuming and costly. What you often need is the ability to make tradeoffs between various options very quickly and early, before you actually make very specific design decisions. At these stages, high accuracy and quantitative results are generally unnecessary, and it’s most valuable just to get rough estimates of where to focus from a thermal perspective. I’d like to share with you a simple method to do just that. This article outlines the approach and parameters, teaches you how to approximate your system, and gives guidance on what to do with the results.

Please note that the resistor approach shown here is often used (and some would say overused) quantitatively, by using resistor networks to calculate the actual component junction temperature. While this can be done successfully, the big challenges that must be considered are how well the values being used are actually representative of the specific system. This must include interaction with other components, and the right representation of ambient temperature.

What we do show here is how to use the resistor approach more qualitatively, in order to make quick and early design decisions and tradeoffs. You may be familiar with the resistor network approach, it’s certainly not new. But hopefully you can get a fresh view of how valuable it really can be as a quick and dirty method.

The thermal resistor network

Heat flow through a thermal system is often represented using electrical analogies of resistances. In the equivalent circuit:

- Thermal resistance (theta) is the equivalent of electrical resistance (R)
- Heat flow (Qdot) is the equivalent of current flow (I)
- Temperature drop (delta-T) is the equivalent of voltage drop (delta-V)
- And delta-T = Qdot * theta is the equivalent of Ohm’s law (delta-V = I * R)

Using this analogy, **Figure 1** illustrates a basic resistor network representation of the thermal path from a component, through a system, and out to the ambient environment above and below it. You may recognize some of the terms, but here is a brief explanation of each, from top to bottom.

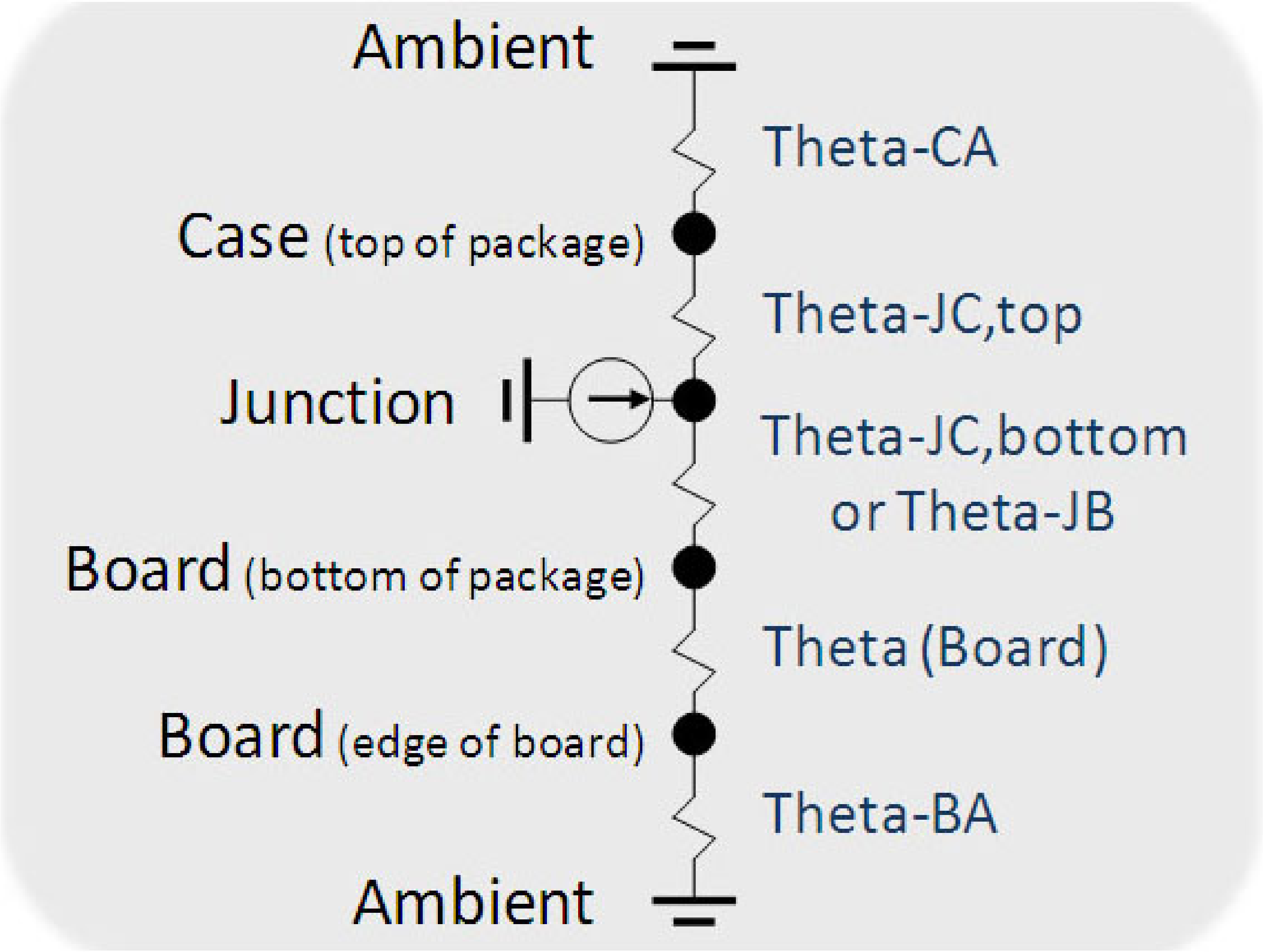


Figure 1: resistor network representation of thermal paths from component to ambient.

- Theta-CA = thermal resistance from the case of the component to the ambient environment
- Theta-JC,top = thermal resistance from the junction of the component to the top case
- Theta-JB (or in some cases Theta-JC,bottom) = thermal resistance from the component junction to the component bottom (or board very near to the component).
- Theta (board) = thermal resistance of the board, from near the component to the rest of the board
- Theta-BA = thermal resistance from the board (as a whole) to the ambient environment

Using the resistor network to approximate a component in your system
Now that we have these terms established, let's see what this can tell us about a given system. Before we even consider any Theta values, and without ever going for really accurate values of them, we can get a lot of value. Here are some quick considerations:

- The complete thermal path is represented in this network. So any thermal design factor is (and must be) captured somehow in one of these resistance values. For example, improving the airflow in a system generally reduces the values of Theta-CA and Theta-BA.

- Heat flow is based on the ratio of resistances. So if the thermal path up is higher resistance than the path down, most of the heat will flow down, and vice versa. For example, Theta-CA usually is very high, meaning that most heat flow is usually down.

- The resistors in each path add up to the total serial resistance of that path. So to improve one of the thermal paths (up or down), the biggest impact will result from addressing the highest resistance in that path.

Going one step deeper, let’s look at each of the five resistors in typical components and systems. We’ll briefly consider their magnitude as LOW, MEDIUM, or HIGH, and discuss typical factors that affect them:

- Theta-CA: This resistance is generally HIGH, on the order of 100’s of C/W. This is because it is limited by the convection and radiation off of the top of the component, which is thermally very small. This means that most of the heat flow from a typical component is through the bottom thermal path. The only way to make Theta-CA a significantly lower value is to add a conduction path to the top of the component. This can be accomplished through a heat sink, or a connection to a metal chassis in the system, and can bring the Theta-CA value down to values on the order of 1-50 C/W.

- Theta-JC,top: Theta-JC,top is generally SMALL, often on the order of 0-20 C/W, and is a function of the component construction, including its size and whether the top of the component is metal or plastic. Given the typically high value of Theta-CA, Theta-JC,top is usually unimportant. It only matters for components which have a heat sink or chassis connection. When needed, this value can be easily provided by the component supplier, and is not easy to modify without a completely new component packaging method.

- Theta-JB (or Theta-JC,bottom): This resistance is generally MEDIUM, on the order of 0-50 C/W. It is a function of the component construction, including its size and materials. This value also can be easily provided by the component supplier. It cannot be dramatically changed without changing the component packaging size or method, but can sometimes be improved by 10-20 percent with advanced component packaging features, if needed.

- Theta (board): This resistance is generally MEDIUM, on the order of 0-50 C/W. It is a function of the PCB design, and the biggest factor is the design of the vias and planes near to the component. It is important that the thermal path from the component (which is usually tied to the ground net), is connected to as many vias and planes as possible, and that those planes have some continuous paths going away from the component. Often it can be easy to improve this thermal resistance by 10 percent or even as much as 50 percent, by simply making sure the PCB design considers these factors.

- Theta-BA: This resistance is generally MEDIUM, on the order of 10-50 C/W. It is mostly a function of the end system. It can be dramatically improved by adding forced airflow or conduction connections to a metal chassis. It often can be improved by 10-30 percent with improvements in the component layout, small chassis connections, or small changes to the physical system design for better natural air movement.

Using this approach for “quick and dirty” thermal assessments
This resistor approach is clearly a very simplified approximation of complex systems, so to use it quantitatively requires a lot of detailed calibration, and may not be practical. But looking at the resistances qualitatively gives a great view and opportunity to see where to focus. Using the descriptions above, **Figure 2** is what the thermal resistances of a typical component in a typical system look like.

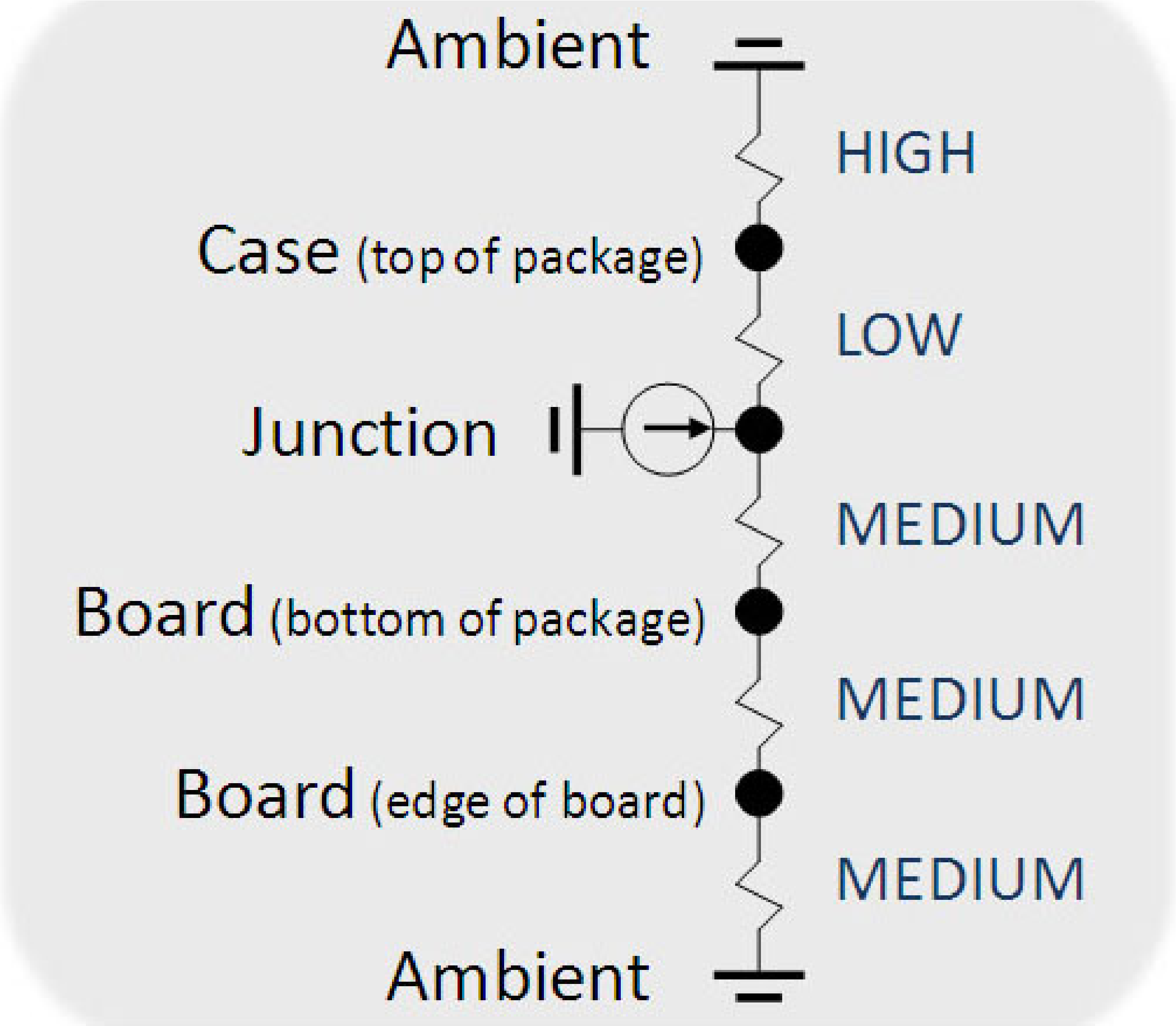


Figure 2: Resistance values for a typical component in a typical system.

What does this mean for early system considerations?

- Heat flow is generally through the bottom path, so this is where you should focus.

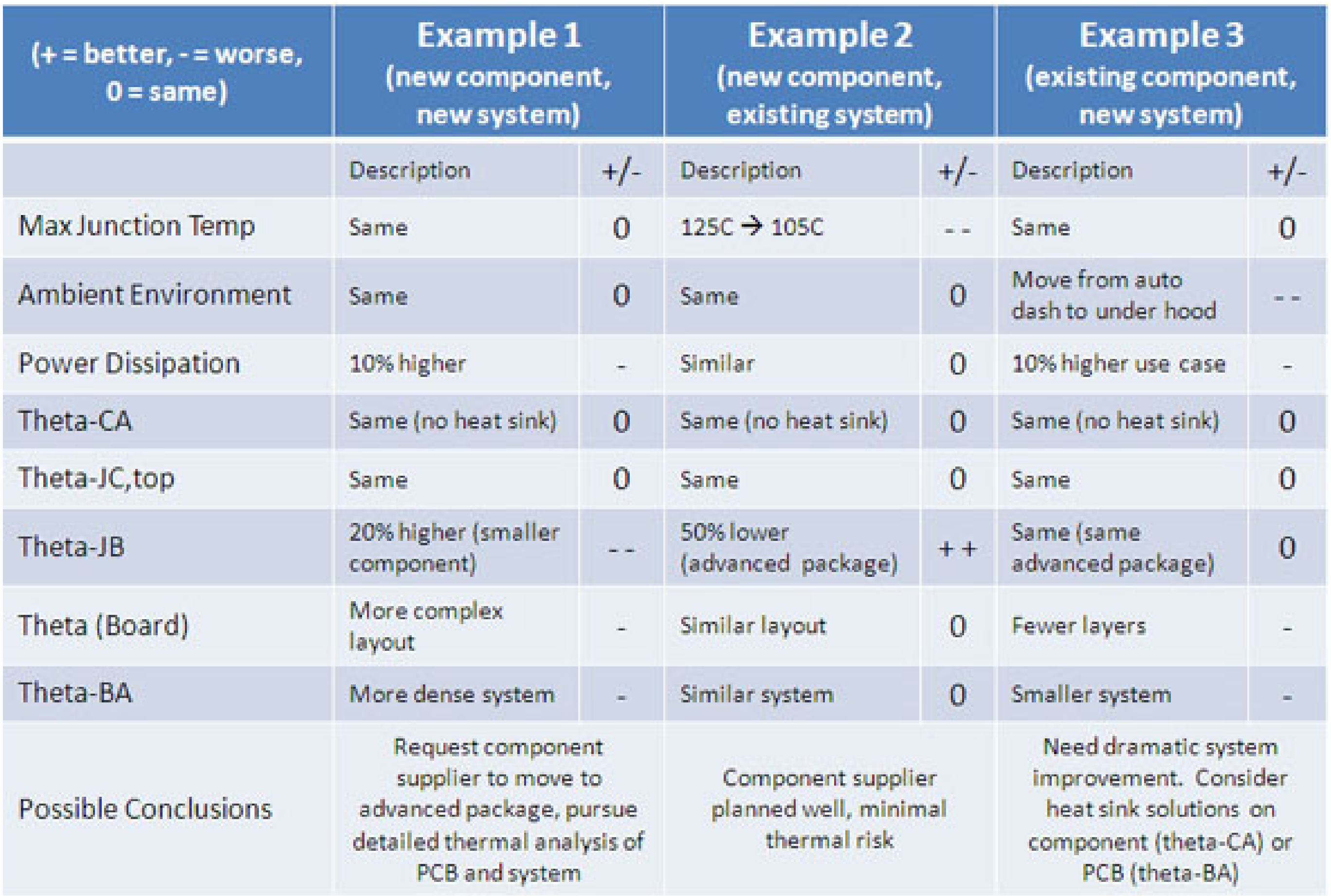
- You need to get some estimate of which of the bottom resistances are dominating the bottom thermal path, and address those first.
- Improvements to the component, printed circuit board (PCB), or system may not be highly impactful, if they are not the biggest contributor to that total resistance.
- You probably only need to improve the top thermal path in cases where the bottom path can’t get low enough. The only way to do that is to add a heat sink or chassis connection to address Theta-CA.

The next level of detail is to get a rough estimate whether the system thermal resistance may be sufficient for the temperature requirements of the component of interest. A good way to do this is to look at an existing component and system, which is similar to the new component and system of interest. This allows you to start from a point of confidence based on well known temperature and power dissipation profiles that are known to be okay.

Then, you can consider all the changes from the previous example to the new one. If the component power dissipation goes up or max component temperature goes down, then the total thermal resistance must reduce. If the system gets smaller, then Theta (board) and Theta-BA increase. If the component package changes, its Theta-JC,top and Theta-JB change and the magnitude can be provided by the component supplier. If a heat sink is added or removed, then Theta-CA and, thus, the top thermal path change dramatically.

All of these changes can be easily considered and mapped into their rough impact on the resistor network. They can be classified by the level of change as compared to the existing example. Then their net effect can give a view of whether small, medium, or large changes are needed to the component or system in order to ensure effective thermal performance.

Table 1 shows three example scenarios. In each of these, a quick assessment is done of the changes planned, as compared to an existing component and system. The assessment includes classification of the key factors, and the qualitative conclusion in each scenario.



(+ = better, - = worse, 0 = same)	Example 1 (new component, new system)		Example 2 (new component, existing system)		Example 3 (existing component, new system)	
	Description	+/-	Description	+/-	Description	+/-
Max Junction Temp	Same	0	125C → 105C	- -	Same	0
Ambient Environment	Same	0	Same	0	Move from auto dash to under hood	- -
Power Dissipation	10% higher	-	Similar	0	10% higher use case	-
Theta-CA	Same (no heat sink)	0	Same (no heat sink)	0	Same (no heat sink)	0
Theta-JC,top	Same	0	Same	0	Same	0
Theta-JB	20% higher (smaller component)	- -	50% lower (advanced package)	+ +	Same (same advanced package)	0
Theta (Board)	More complex layout	-	Similar layout	0	Fewer layers	-
Theta-BA	More dense system	-	Similar system	0	Smaller system	-
Possible Conclusions	Request component supplier to move to advanced package, pursue detailed thermal analysis of PCB and system		Component supplier planned well, minimal thermal risk		Need dramatic system improvement. Consider heat sink solutions on component (theta-CA) or PCB (theta-BA)	

Table 1: Example scenarios assessing key thermal factors.

Summary

As you can see, it is possible to use a basic resistor network to assess thermal performance quickly in the early stages of a component or system design. The resistor network as explained above can be easily understood by anyone involved in the design. The concept itself can help to conceptually understand where to focus in typical systems. And a quick assessment of a specific component and system can allow for effective communication of thermal factors to be considered throughout the design effort. The net result can be faster, cheaper, and of course cooler electronic products!

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About the Author

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