Designing Mobile Devices for Low Power and Thermal Efficiency

October 2013

Qualcomm Technologies Inc.

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1   Executive summary

Today, consumers demand more from their mobile devices including seamless 3G/4G broadband connectivity and leading features such as high-end digital camera functions and HD audio, but their number one requested feature is still longer battery life.[1] Delivering the horsepower required to enable the breakthrough experiences consumers want from their smartphone is a major challenge because these devices are some of the most power- and thermally-constrained devices around. This requires a mobile-centric approach that ensures the optimal balance of performance and power.

This approach is radically different from the PC-centric approach in which the central processing unit (CPU) is responsible for the vast majority of processing tasks; a fan and heat sink are used to dissipate heat; and the device has a constant connection to a power source (wall plug). Qualcomm Technologies, Inc. (Qualcomm Technologies) believes that achieving low power consumption and thermal efficiency in mobile is only possible by taking a holistic approach to power management across the system, moving away from a CPU-centric model, and instead utilizing highly efficient, specialized mobile processing engines that are specifically designed to perform a given task or enable a user experience at optimal power and thermal levels.

This paper details how Qualcomm Technologies takes a holistic system approach, which is best achieved by custom designing the key technology blocks and the entire system-on-chip (SoC). This system approach involves optimizing for both power and thermal at four key levels:
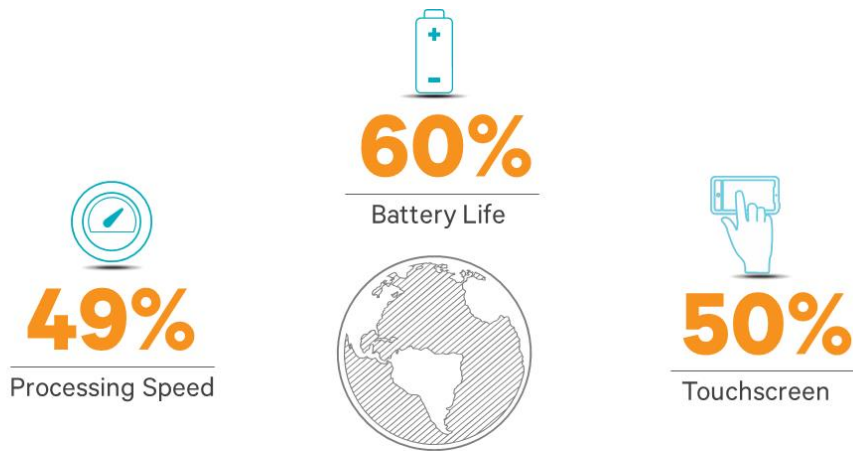
1. **Specialized processing engines**. We custom design specialized processing engines and other key components, such as, the power management integrated circuit (PMIC), radio frequency (RF) chips, and more.

2. **Smart integration**. We smartly integrate technology blocks and design the system architecture.

3. **Optimized system software**. We tightly integrate the software to the hardware.

4. **Device-level optimization**. We carefully consider all other components on the mobile device and optimize the operation of the complete solution.

2   Mobile trends and consumer expectations

Now more than ever, consumers are demanding more from their mobile devices. They want sleeker form factors, faster connectivity, richer and bigger displays, and better multimedia capabilities. In turn, their devices are demanding more processing horsepower. To meet this demand, the mobile industry is continually innovating to deliver the increasing performance required by these breakthrough mobile experiences, while maintaining thermal efficiency and delivering longer battery life. Despite the advancements in device capabilities, long battery life remains the number one requested smartphone feature by consumers.

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[1]   According to a 2013 survey commissioned by Qualcomm Technologies, Inc., 60% of surveyed consumers rank battery life as the #1 requested smartphone feature.

49%
Processing Speed

60%
Battery Life

50%
Touchscreen

#1 End User Requested Feature = Better Battery Life

Figure 1: Survey results: Most important smartphone features[2]

When it comes to display, the trend is "bigger is better." For enhanced visual experiences, such as for gaming and video, consumers are increasingly demanding bigger screens with higher resolution. Screen resolution has increased approximately 25x from 2006 to 2012 on smartphones.[3]
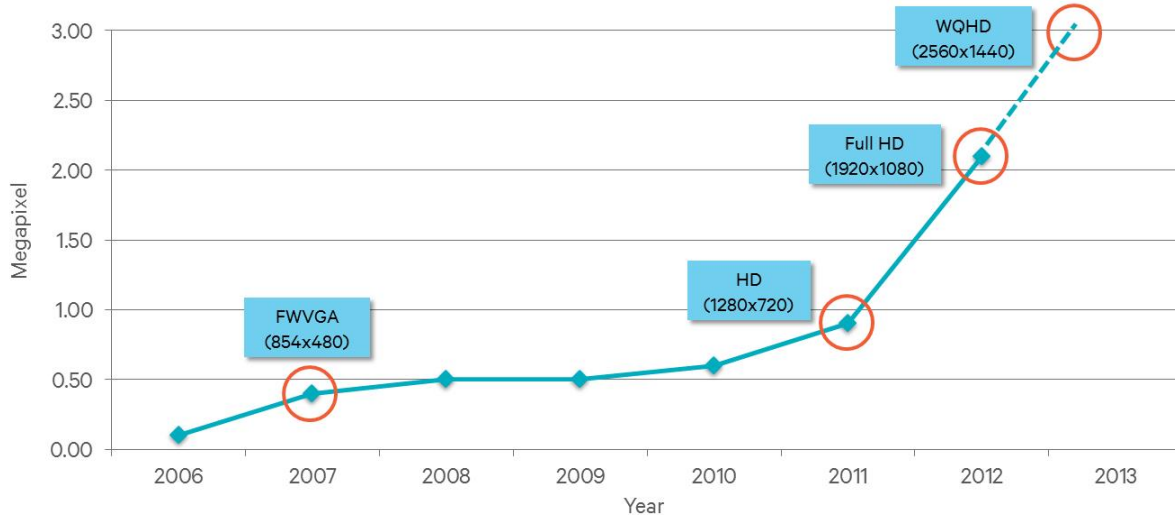

Figure 2: Increasing maximum resolution in smartphone displays

The ability to support 25x more pixels requires a lot more processing capabilities, especially for applications which require a lot of graphics rendering, such as gaming. Correspondingly, memory

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[2] Survey question: For your next [smartphone /mobile phone] purchase, which of the following features would drive your decision to select one phone over others? Select all that apply.

[3] Source: Qualcomm Technologies internal data.

bandwidth requirements have also increased significantly to keep up with the dramatic increases in pixels and new usage models.

Also, consumers are increasingly using their smartphone as a multi-functional device that replaces multiple consumer electronic (CE) devices of the past. They use it as a gaming console, camera, audio and video player, personal navigation device, and to handle many computing functions. Consumers increasingly expect smartphones to perform these functions equally good or even better than function-specific CE devices and PCs. They have not only come to expect smooth web browsing, advanced camera capabilities, and immersive graphics to improve with each next generation smartphone, but they also expect new usage models and experiences such as augmented reality, contextual awareness, gesture control, and always-on experiences.

With the increasing computational requirements for the SoC, the challenge is to deliver all these great experiences in a sleek, thin mobile device that stays cool and has a long battery life. The form factor of a device has a significant impact on its temperature level.[4] Thermal efficiency for smaller form factors is more challenging. Therefore, smartphones with thin form factors usually pose a tougher problem than tablets that have more room inside.

This calls for a design approach that enables advanced user experiences, while delivering longer battery life and thermal efficiency. The old CPU-centric approach does not apply any more. Mobile has unique requirements and success requires a different design philosophy.

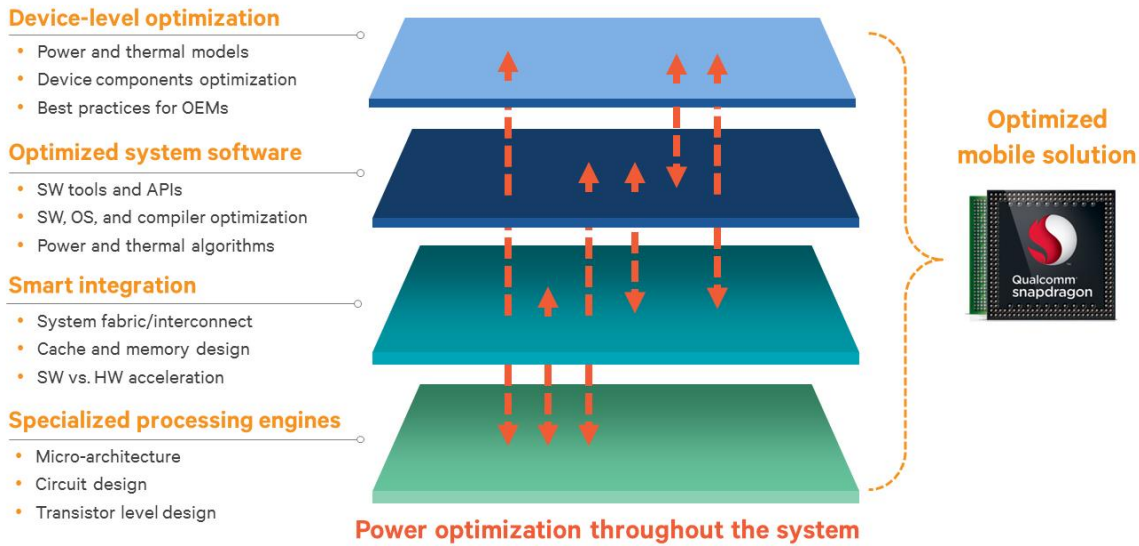# 3 System approach for power-optimized design

A holistic approach to power management and system design is required to achieve the lowest power and the optimal thermal efficiency for mobile devices. This involves gathering the key requirements and constraints for the mobile device, making the appropriate tradeoffs, and then designing for low power and thermals across the whole system, while enabling a highly responsive and robust user experience on the device.

Designing for mobile requires a deep understanding of consumer expectations, needs, and behaviors, both in terms of how they are using their mobile device today and in the future. This understanding guides system designers to optimize their designs based on the performance, power, and thermal requirements of key use case scenarios. It is essential to make the right tradeoffs between these factors, taking into account the overall effect on the system in various usage models.

At Qualcomm Technologies, we invest in the key technology blocks in the SoC. This allows us to custom design our SoC to effectively address emerging mobile experiences and consumer trends. Based on key usage models, we optimize our SoC solution for performance, power, and thermals. To deliver the lowest power design for mobile devices, optimization is performed across the entire system, which has four key elements:

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[4] The heat generated in a device is directly related to the amount of energy dissipated per unit area, which is also called energy density.

Figure 3: Holistic system approach to low power and efficient thermal design

1. We custom design our own 3G/4G modem, CPU, graphics processing unit (GPU), digital signal processor (DSP), image signal processor (ISP), display engine, video engine, sensor engine, and other specialized processing engines. We optimize the architecture of these processing engines for performance, power, and thermal without being limited to generic, licensed intellectual property (IP) blocks.

2. We smartly integrate key technology blocks and custom design our own system architecture, including interconnects, caches, memory systems, and more. This is critical for the processing engines to work well together.

3. We optimize the system software to take advantage of power saving hardware features and to make intelligent power management decisions.

4. We consider all the components that make up the mobile device, not just the SoC, and optimize for both power and thermal efficiency.

Between each of these layers there are also dependencies, represented by the arrows in the image above. The holistic view of the system allows architects to evaluate key constraints, requirements, and dependencies, and then to make the most appropriate tradeoffs for mobile. By custom designing across the system, Qualcomm Technologies can make the appropriate design tradeoffs and use that insight to deliver a solution truly optimized for power and thermal.

No one custom designs to the same extent as Qualcomm Technologies in taking a holistic system approach to mobile. Many mobile silicon vendors typically license third-party processing engines and then integrate them. The downside to this approach is evident when trying to integrate these generic, pre-defined processing engines together. In addition, this approach to SoC design may not be optimal for addressing the requirements of a specific product tier or use case.

3.1 Specialized processing engines

To optimally address a specific product tier, quickly change a roadmap for a new user experience, or innovate in other new directions, a silicon vendor must invest in the key technology building blocks. Qualcomm Technologies custom designs best-in-class processing engines that are specifically optimized for the power and thermal constraints of mobile devices. For example, we custom design our own modem, GPU, DSP, CPU, camera, sensor engine, video engine, and much more.
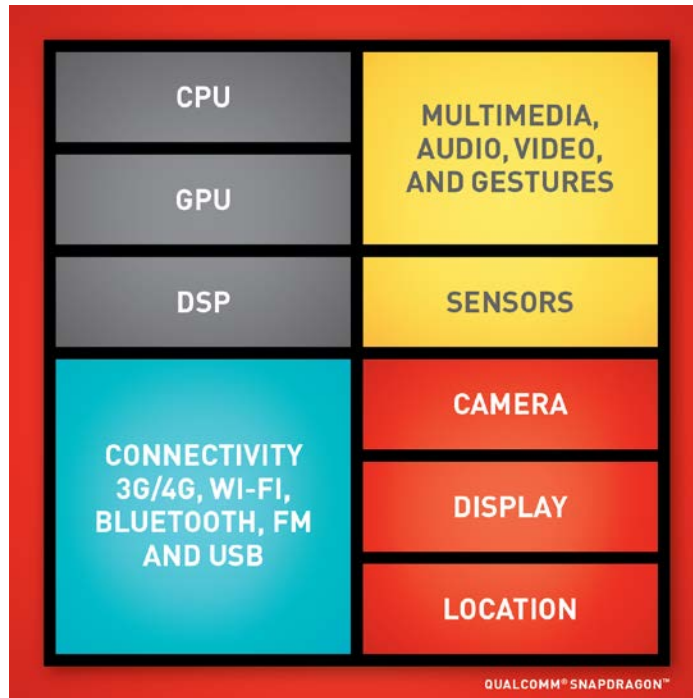

Figure 4: Processing engines in a Snapdragon SoC

We custom design processing engines at different levels: transistor, circuit, and micro-architecture.

- At the **transistor** design level, we work closely with foundries to ensure that the transistor characteristics meet the performance requirements at the lowest power, to enable the best possible experience.

- At the **circuit** design level, we custom layout key portions of a processing engine rather than just using generic synthesis results.

- At the architecture or **micro-architecture** design level, we custom design each processing engine within a thermal and power budget for the key mobile use cases to achieve maximum performance per watt. Based on these constraints, we innovate and develop new power savings techniques. For example, we design our Krait CPU with asynchronous symmetric multi-processing (aSMP), which allows us to independently control the voltage and frequency of each CPU. [5] Lacking the aSMP feature, several other vendors' SoCs must run each CPU

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[5] The Krait CPU is only included in certain tiers of the Snapdragon processor.

at the same frequency and voltage, which wastes power. For more examples of SoC micro-architecture innovations from Qualcomm Technologies, click here.

Quad Core Krait™ CPU

Voltage 1 Voltage 2 Voltage 3 Voltage 4

| CPU1 | CPU2 | CPU3 | CPU4 |

Clock 1   Clock 2   Clock 3   Clock 4

Other Mobile CPUs

Voltage
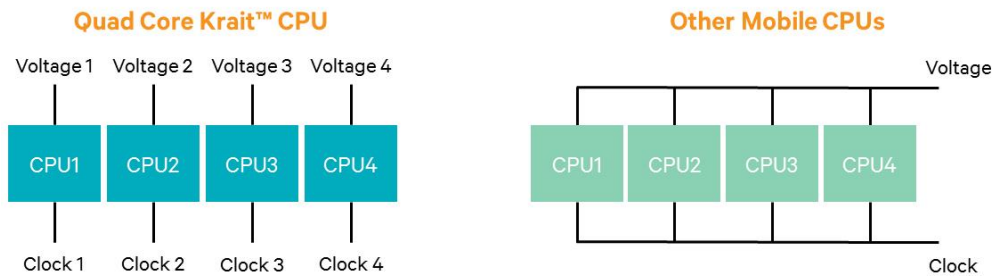
| CPU1 | CPU2 | CPU3 | CPU4 |

Clock

Figure 5: aSMP vs. typical SMP implementation

We custom design these diverse, specialized processing engines because no single processing engine can optimally perform every task. Utilizing specialized processing engines that truly excel at completing a particular task enables Qualcomm® Snapdragon™ (Snapdragon) to deliver higher performance at lower power. For example, offloading a computer vision algorithm, such as feature detect, from the CPU (which is not optimized for signal processing) to the DSP (a digital signal processor) results in significant power savings.

This is what mobile heterogeneous computing is all about. It is about opportunistically choosing the most suitable processing engine for each task. At Qualcomm Technologies, we make sure that all these processing engines work well together. We understand each processing engine's strengths and make sure that we run the appropriate workload on the most suitable processing engine.

In fact, offloading as much functionality from the CPU when it makes sense is the objective, since specialized processing engines are often more power efficient for many tasks. Specialized processing engines can be an order of magnitude more power-efficient than using the CPU alone. For example, video playback easily delivers up to 5x the power savings by running on a specialized video decode engine.[6]
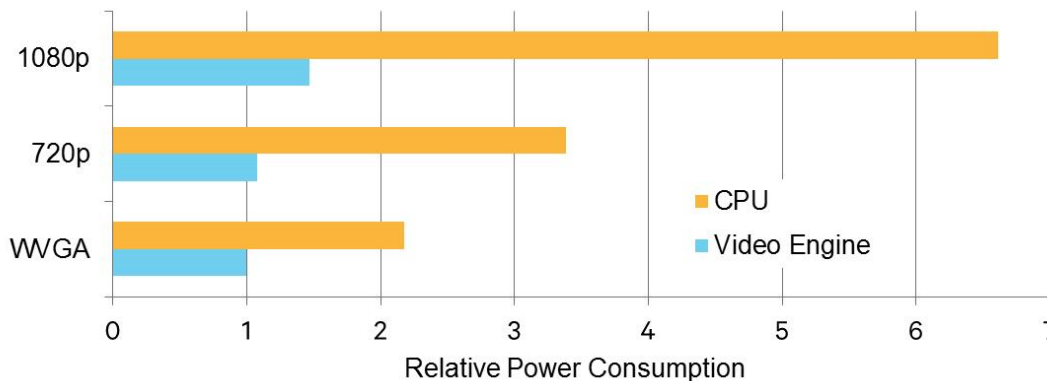

Relative Power Consumption

Figure 6: Relative power consumption of video playback on CPU vs. a specialized video processing engine

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[6] Source: Qualcomm Technologies internal data.

In addition, because we custom design the architecture of many of our specialized processing engines, we can easily evolve them to deliver emerging user experiences at the lowest power, and often with higher performance. A good example of this is the Hexagon DSP, which was originally designed for audio and voice applications. However, the current version of the Hexagon DSP has added additional instructions to its instruction set architecture (ISA) to very efficiently run additional use cases, such as image enhancement, computer vision, augmented reality, video processing, and sensor processing.

3.2 Smart integration

The SoC includes many different processing engines that are integrated into a single piece of silicon. There is a trend towards integrating more and more onto the SoC. What differentiates a silicon vendor is not just how much they integrate, but how they integrate. Smart integration is much more than stitching together generic third-party IP blocks. The level of integration varies amongst silicon vendors depending on their IP technology and design capabilities.

Beyond the obvious benefits of integration, such as area and cost savings, smart integration results in lower power and thermals. The insight gained by custom designing both the individual processing engines and system architecture allows the SoC architects to make the appropriate design decisions and tradeoffs amongst the many dependencies throughout the system. This insight gives a true system view and the ability to propagate features, accurately simulate use cases, and quickly respond to the market demands.

In designing our own system architecture, we analyze the workloads of emerging use cases to deliver an SoC that is optimized for low power and thermal efficiency. This allows us to make the right design tradeoffs for mobile, and to effectively provide the needed rich mobile experience at the lowest possible power. We simulate use cases at the chip level, analyze how they will work on the diverse processing engines, and then optimize accordingly.

In addition to simulating for performance, we carefully create accurate power and thermal models for each processing engine, in order to simulate key use cases for thermal and power issues. Discovering these issues early in the design process (during the system architecture stage) allows us to find smart solutions rather than band-aid solutions. It also gives the processing engine architects the right constraints and direction to design the lowest power implementation. Because of this, we are able to provide high peak performance capabilities tempered with a careful set of performance points to back off as needed to meet the constraints of any mobile device design.

In addition, we purposely design the SoC with the ability to manage both the power and thermals across the chip. The floor plan of the chip is carefully laid out to take into account the power and thermal characteristics of the processing engines. This reduces the possibility of heat being concentrated in a particular part of the SoC and leading to hotspots on the surface of the phone. In addition, temperature sensors are embedded throughout the SoC strategically so that hotspots can be quickly detected and mitigated when necessary, which results in a better user experience. It takes a deep understanding of the processing engines to optimally place the sensors, and a silicon vendor using third-party IP blindly may not have that knowledge.

We also use several design techniques to address the power and thermal challenges. For example, we dynamically vary the clock frequencies and voltages to individual processing engines that are active, and turn off processing engines that are not being used, so that we provide the appropriate performance based on the needs of the running application(s). Various other power and thermal optimization techniques are used across all the processing engines of the SoC (e.g. envelope tracking for the modem).

Having a system view also allows us to consider the full capabilities, both the strengths and weaknesses, of our own custom-designed processing engines. By understanding these capabilities, we know when we should add or remove functionality from a processing engine to meet the desired user experience. By understanding the processing engines capabilities, we also know the best way to distribute the workloads of different use cases to the most appropriate processing engines, which saves power.

One of the biggest advantages of having a system view is that it allows system architects to optimize the design for all the shared resources on the SoC, like memory, system fabric, and interconnects. Simulating use cases with heavy concurrency and high memory bandwidth quickly reveals the importance of having a memory controller that delivers high quality of service and efficient bandwidth. Use cases that require going off-chip to dynamic random-access memory (DRAM) for heavy bandwidth often incur heavy power penalties, and thus thermal penalties. By reducing DRAM traffic through smart caching, architecture features, and efficient memory controllers, significant power is saved.

3.3 Optimized system software

Taking advantage of all the great power saving features implemented in the SoC requires that software and hardware are tightly integrated. Intelligent software uses the power saving features implemented in different processing engines to manage both power and thermal to meet use case requirements. In order for applications to take better advantage of the power savings, the entire software stack must be optimized for the hardware.

The software stack generally includes elements such as the drivers, runtimes, operating system, and APIs. Having a system view allows a silicon vendor to make the appropriate design decisions in the system architecture and the processing engines, based on the requirements coming from the software stack, which results in an optimal solution.

At Qualcomm Technologies, we efficiently implement the software stack to take advantage of the power saving features in the hardware. We develop many algorithms to make intelligent power, thermal, and performance management decisions. By taking a holistic view of power and placing all the right hooks in the hardware, such as the temperature sensors and processing engine statistics, the software is able to make intelligent decisions that deliver the highest performance at the lowest power.

At the consumer level, Qualcomm Technologies has developed the Snapdragon BatteryGuru application. The Snapdragon BatteryGuru is designed to intelligently "learn" usage patterns on Snapdragon-powered smartphones. The application then uses that data to optimize battery life

without disabling the smartphone's functionalities. Please refer to future power blogs for more information.

3.4 Device-level optimization

Overall system power is the key to device efficiency. A silicon vendor that optimizes for power only at the SoC level without considering all the other components on the device will not be able to deliver the best low power solution. Power and thermal touches nearly every aspect of the system design.

Qualcomm Technologies deeply understands the main components on the device and how to appropriately measure the power and thermal impacts. In fact, besides designing the SoC, we also custom design the PMIC, audio codec, and RF chips. Custom designing the PMIC specifically for the Snapdragon processor allows for very tight control of power saving features like aSMP, and also allows us to meet specific latency and power sequencing requirements of the SoC.

For OEMs, selecting device components is a crucial decision. At the device level, there are several power hungry components to manage, such as the display, power amplifiers, and DRAM. For example, the display is often the most power hungry component of the system. It is essential that the display subsystem within the SoC reduces the display power with innovative techniques. Qualcomm Technologies uses content adaptive backlight (CABL) and frame buffer compression (FBC) to save power. CABL with temporal filtering alone delivers up to 30 percent power savings with no visible artifacts.[7] FBC, a Qualcomm Technologies proprietary compression scheme, compresses display data by up to 50 percent in a visually lossless manner before transmission to the display.[8]

In addition, Qualcomm Technologies spends a tremendous effort in developing comprehensive power and thermal models for the main components on the system. Beyond developing models for the Snapdragon processor, PMIC, audio codec, and RF that we custom design, we also develop models for the components that we do not design, such as the memory, printed circuit board (PCB), power amplifiers, capacitors, heat spreaders, battery, and materials used throughout the system. A reliable model of the entire system allows us to develop and test new algorithms on our SoC that most effectively reduce power and dissipate heat. It also allows us to develop thermal and power management software that is flexible enough that it can be customized to work on a variety of system designs.

Developing these system models well before chip tapeout also allows us to discover issues not only in our chip design but also in system designs, early in the design process. For example, running power and thermal simulations allow us to find hotspots early so that we understand how to layout the system components in a way that dissipates heat more equally throughout the entire device, with the heat being removed more equally through the display and backside. It takes only one hotspot for the device to throttle the performance and thus have a flawed system design. Whether the hotspot is on the skin of the device, the SoC, the memory, or any other component, performance throttling will degrade the user experience.

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[7] Source: Qualcomm Technologies internal metrics.

[8] Source: Qualcomm Technologies internal metrics.

Selection of materials, which are used throughout the system, is another essential part of the system design for proper heat dissipation. Although OEMs make the final choice on the industrial design and the other internal materials, Qualcomm Technologies carefully studies the materials to understand how to best spread heat equally throughout the system.

The thermal effusivity of materials determines the rate at which heat can be exchanged with its surroundings, so it is another key consideration in system design for dissipating heat. In general, a system that does not dissipate heat well and maintains a high temperature will result in higher leakage power in silicon, which produces more heat, which again causes even more leakage— unless the performance is throttled. To prevent this vicious cycle, controlling leakage power is essential, especially as leakage power can get worse as the silicon process node shrinks. At high temperatures, leakage power can get as high as the active power of the silicon. Also, running system components at high temperatures also affects their reliability and shortens their lifespan.

Based on all this experience, knowledge, and modeling, Qualcomm Technologies has developed key insights and best practices for low power and thermal efficient system level design. We partner with our OEM customers to implement sound power and thermal solutions to deliver a device with the best user experience.

4 Conclusion

To address the increasing challenge of delivering higher performance in devices with power and thermal constraints, a mobile-centric design approach is essential. Qualcomm Technologies takes a holistic system approach to power and thermal management. By designing specialized processing engines, smartly integrating them, and optimizing both the system software and across the device, mobile SoCs from Qualcomm Technologies deliver the optimal balance of power and thermal efficiency, enabling mobile devices to deliver the best user experience.