The convenience of wireless charging: It's just physics White paper

By Mark Estabrook, MediaTek

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New hope emerges amidst standards war

A storm is brewing in the world of wireless charging. Over the past few years we have seen a number of consumer products in the market from Powermat and members of the Wireless Power Consortium (WPC) based on inductive technology, sometimes also referred to as tightly coupled technology. Powermat's efforts have led to the formation of another consortium called Power Matters Alliance (PMA) ostensibly to compete with the large, well organized and well-funded WPC. Although the nod goes to the WPC for the sheer number heavy weight companies supporting the specification, including MediaTek, Nokia, Samsung, LG, Verizon, Philips, and NTTDocomo, the PMA has also lined up some heavy hitting supporters including MediaTek, AT&T, Google, Proctor & Gamble, TI, NXP and Starbucks, with many more joining recently. The PMA specification offers some interesting capabilities around networking that can support active monitoring and metering of power to each device. This feature is attractive to potential providers of charging services, like Starbucks. The PMA, with MediaTek's support, is also aggressively pursuing an integrated dual mode approach to wireless charging, bringing the resonance and inductive technologies under one unified and interoperable specification.

While industry pundits debate which of the inductive specifications will win the market acceptance battle, other companies and groups, like MediaTek, A4WP, and PowerbyProxi, are talking about a newer technology commonly referred to as resonance but more accurately described as highly resonant loosely coupled technology. The providers of resonant solutions have yet to release a product, but are showing compelling demonstrations at tradeshows and online.

None of these inductive or resonant specifications or demonstrations support, or will support products that are directly compatible with the other. So it's not just a replay of the BetaMax vs. VHS saga. It's going to be an all-out street fight. Or is it? Will one technology or specification rise to the top?

While the inductive solutions have a strong head start in the marketplace, resonant solutions may offer a significantly better user experience at lower cost. Geoffrey Moore in his highly acclaimed book "Crossing the Chasm" describes the need for early products and technologies to hit several key milestones in order to transition from the early adoption phase, where interest is high but volumes are small, to the early majority phase, where a more discerning customer resides but volumes are high. To "cross the chasm" to success, a product must be easy to use, widely available, and relatively low in cost. The consumer is looking more for value and less for the "wow" factor. Inductive solutions today have created a "wow" impact in the market and found early success with early adopters, but suffer from severe limitations that are inherent in the physics of how inductive solutions work. Can inductive systems provide ease of use and low cost? We don't think so for the majority of consumer devices wanting to be wirelessly charged (e.g. phones, BT headsets, tablets, phablets, cameras, smartwatches, notebooks, etc.). This paper tries to give some background to the underlying physics behind inductive and resonant technologies that lead directly to their ability, or not, to cross the chasm of market success.

But before we compare and contrast the inductive and resonant technologies, we should first answer the simple question of why wireless charging makes sense at all. Compared to wired charging, all wireless charging technologies have lower efficiency, higher cost, and may not be able to charge at the same rates of power. So there needs to be a compelling reason to want wireless power beyond just the “wow” factor.

Operator strategies for power management in LTE phones

Operators have been working closely with the many of the players in the mobile phone eco-system to develop strategies to lessen power consumption, but the reductions are not enough. The operators are looking to the promise of convenient and frequent charging with wireless power as one more key strategy for keeping the phone battery full. Note that Verizon, AT&T, NTTDocomo, Softbank and KDDI are all early adopters of both LTE handsets and wireless power.

You might think that consumers will not accept hourly charging in place of daily charging, but this is precisely the hope of wireless charging. Let’s face it, plugging a USB cable into your phone is not that hard. If you only do it once a day, is it really worth the US$50 to $75 per phone you will pay for the convenience of placing the phone on a charging pad rather than plugging in the USB cable? Probably not. So what the operators are looking for is a way for customers to easily charge their phones without thinking too much about it. Charge it at home, in the car or subway train, in the coffee shop and in your office. Place the phone in the right spot anywhere and let it charge. But you need a couple of things for this to be an experience embraced by the consumer: Interoperability between chargers and receivers (phones, tablets, etc.), and a compelling user experience that is far better than plugging in a USB cable. A good user experience includes:

- **Ease of use:** Placing the phone on or near a charging pad or surface without worrying about alignment or movement of the device from bumps or vibration.
- **Reasonable power:** The device should charge at a rate similar to wired charging or better.
- **Low cost:** The benchmark is the cost of a USB cable, which wireless chargers will never meet. Consumers, however, will always weigh the cost of a cable against the convenience of wireless charging.
- **Interoperability:** Single device: Any phone should charge on any charger.
- **Multiple devices:** A single charger should charge all your devices concurrently (at least phones, headsets, and tablets).
- **Safety:** There can be no safety risk in terms of heating or emissions.
- **Environmentally friendly**: Several markets and cultures demand environmentally friendly solutions that do not consume excessive power.

Perhaps a truly disruptive technology is required to provide these compelling user experiences.

Why inductive charging may underwhelm consumers

Powermat launched its first products for wireless charging in 2009. Powermat technology is the basis of the specifications being developed by the Power Matters Alliance (PMA). The Wireless Power Consortium (WPC) members launched products starting in 2011 in Japan. Both products have seen early successes with market adoption that is due, at least in part, to the “wow” factor of wireless charging. An important question remains as to whether the technology is disruptive and compelling enough to cross the chasm between early adopters and early mass market adoption.

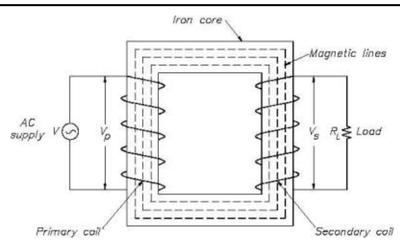

Figure 1: Transformer model

Source: http://nuclearpowertraining.tpub.com/h1011v4/css/h1011v4_48.htm

In attempting to answer this question let’s first look at how inductive charging systems work.

The electrical model of a transformer can be used to describe a system. Transformers have primary and secondary windings and an iron core that couples the magnetic field of the primary into the secondary winding.

The current flowing through the primary coil creates a magnetic field according to Ampere’s law:

$$dB = k\frac{I\ dl\ sin\theta}{r2}$$

dB = change in magnetic flux , I is the current in the wire, dl is the length of the wire, sinΘ is the angle of a point from the wire where the magnetic field is measured, r is the distance to that point, and k is a constant (see Figure 2)[1].

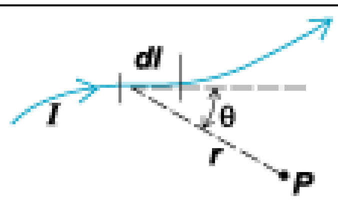

Figure 2: Amperes Law

The primary coil is coupled into the secondary coil via the induced magnetic field. The purpose of the iron core is to help collect the magnetic field around the primary winding and present it to the secondary coil. The induced magnetic field in the secondary coil creates current flow (wireless power transfer) in the secondary coil.

In a tightly coupled wireless charger the principle is the same but with the iron core removed and the use of planar coils rather than windings. Without the iron core the magnetic field must travel across air rather than iron. Air has much lower permeability (ability to pass magnetic fields) than iron by a factor of about 7,000[2]. Therefore the amount of magnetic flux and resulting power coupled into the secondary coil across air is much lower than with iron. In order to get power transfer with any reasonable degree of efficiency (typically about 70 percent DC in to DC out in today’s wireless power systems) the primary and secondary coils must be in very close proximity and in

[1] McGraw-Hill Science & Technology Encyclopedia: Ampère's law.

concentric alignment. This is so that the secondary coil couples to the largest and strongest part of the primary coil's magnetic field. In more specific technical terms, any magnetic flux from the primary that does not couple into the secondary is represented as leakage inductance. Leakage inductance causes energy to be wasted because it presents an impedance to the source coil driver but does not induce voltage in the secondary winding. The increased impedance in the source coil driver causes I^2R losses as the current is increased to maintain charging at target rates in the receiver.

In normal use the leakage inductance would be minimal. But if you try to move the primary and secondary coils away from each other the leakage inductance becomes much greater which we measure as a decrease in coil to coil efficiency. At lower coil to coil efficiency the charger must develop and attempt to send more power leading to higher charger losses for the same delivered power.

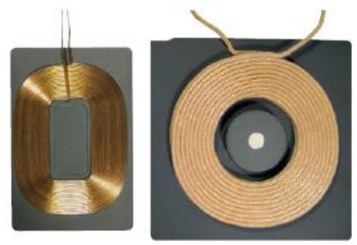

Figure 3: Example Qi primary coil (right) and receive coil (left)

Thus the primary and secondary coils must be arranged in such a way as to always remain "tightly coupled". Typical inductive coils can be seen in Figure 3. Note that the coils are very similar in shape and size. These particular coils are used in a 2.5W smartphone charger.

Primary (charger) and secondary (receiver) coils in tightly coupled wireless power systems are:

- Concentrically aligned
- Approximately the same size
- Used in very close proximity (very little distance between the coils)

How tightly coupled technology is much like that of wired chargers

Looking at these characteristics you can see that tightly coupled systems couple power from a single primary coil to a single secondary coil. This means that tightly coupled chargers are 1:1 charging systems. They charge only one device at a time. Notably, USB charging cables are also 1:1 chargers. You need one charger for every device. If you want to charge more than one device concurrently you will have to use multiple chargers. To charge two phones concurrently you'll need:

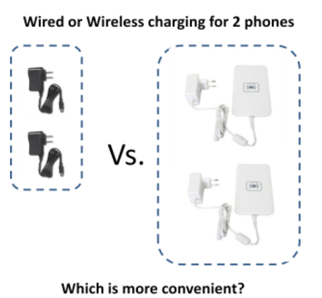

Figure 4: Wired vs. Qi wireless charging for two phones

- Two AC adapters for wired charging
- Two AC adapters and pads for wireless charging[3]

[3] There are some chargers that have multiple charging pads for similar devices and just one AC adapter, but you cannot get away from needing at least one active charging coil for every device.

Based on this fact alone inductive wireless charging does not seem to be a potential disruptive technology that can provide a low cost, convenient charging experience.

How tightly coupled technology constrains design

Finally, tightly coupled charging systems must have the primary and secondary coils placed in very close concentric alignment in a flat plane and remain in very close proximity with each other to charge effectively. The mechanical design of some products don't always allow for easy alignment. Phones and tablets require that the flat coil be placed on the back cover of the device. In most cases that works very well. But other devices like smartwatches and Bluetooth (BT) headsets don't lend themselves to this physical limitation. As we've seen, BT headsets need to use charging cradles that are large enough to accommodate the coil's size. But the secondary coil also has to sit flat on the charging pad rather than just lay on the charging pad in no specific manner. This means that in addition to purchasing a charging pad with an AC adapter, the consumer must also purchase a charging cradle for the BT headset in order to use wireless charging. With most BT headsets you simply plug a mini-USB charger into the headset itself. Which would you prefer? Keep in mind that with tightly coupled inductive 1:1 charging systems you cannot charge both your BT headset and your phone at the same time[4].

Summary on characteristics of tightly coupled inductive solutions

If there is only the requirement to wirelessly charge a single phone then a tightly coupled charger should work quite well. WPC and PMA products have had the benefit of a few years of engineering development that have led to well optimized small footprint, low cost, and high efficiency designs and even some freedom from critical concentric alignment if you use a multi-coil charger design[5] (albeit at higher cost). But to cross the chasm from early adopter to early mass market wireless charging solutions the charging experience should be easy and convenient to the point of being almost thoughtless. This means being able to charge multiple devices at a time, charge different sized devices at optimal power (Bluetooth headsets, phone, camera, tablet, etc.), and to not restrict mechanical designs optimized for consumer convenience and aesthetic value.

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[4] **Some inductive chargers include multiple coils and electronics to support multiple device charging (up to two as per what's on the market, and five as per demonstrations). They are still 1:1 charging systems, but simply combine two or more separate chargers into one package.**

[5] **The charger is able to identify which charger coil is in good alignment and energizes that particular coil to enable 1:1 charging.**

Tightly coupled inductive wireless power solutions have the following key characteristics:

- Inability to charge more than one device at a time
  - **Result:** Consumers must purchase multiple chargers to charge devices concurrently.
- A need for coils on the charger side and the receiver side to be of similar size and shape
  - **Result:** Secondary receiver coils cannot be matched to the receiver device for optimal power delivery. With charges delivering moderate power, low power devices cannot be charged and high power devices can only be charged at the moderate rates.
  - **Result:** Secondary receiver coils cannot be matched to the device for best mechanical fit (size and shape such as circle, square, rectangle, oval, etc.).
- A need for charger and receiver coils to be closely aligned
  - **Result:** Only specific and tightly constrained mechanical designs can be considered. Some devices like Bluetooth headsets cannot practically be charged at all without the use of a separate charging cradle that houses the receiver coil.

The simple laws of physics lead us to certain undeniable facts. Tightly coupled systems have severe limitations in optimally charging more than a single style of consumer device under a single standard, and can only charge one device at a time. No amount of marketing promotion and market hype can change this fact. And as John Adams famously said: "Facts are stubborn things". So what can be done? Will the early success of wireless charging fail to gain momentum and cross the chasm to the mass market?

No. A basic principle in physics comes to the rescue: Resonance. If we could design a system where the secondary coil needs only intersect with a limited number of field lines from the primary coil, then the secondary coil would not have to be aligned precisely with the primary coil, or be the same size. The secondary coil can perhaps even be moved some distance away from the primary coil. And if the secondary coil can move away from the primary coil, then there is the possibility of more than one secondary coil to intersect with the primary coil field lines. This sort of system would be called "loosely coupled". The problem with loosely coupled systems is that the efficiency of the power transfer will be very low since the magnetic flux lines intersecting the secondary coil are fewer and typically weaker than in a tightly coupled system. But there is a principle in physics called resonance that can greatly improve the efficiency of power transfer and can make loosely coupled wireless charging practical. Highly resonant loosely coupled systems can make a truly low cost disruptive charging solution that can cross the chasm to mass market adoption.

The convenience of loosely coupled highly resonant systems

In a loosely coupled system the secondary coil may be coupled to fewer of the magnetic field lines and have a larger distance from the primary coil as compared with inductive coupling. This provides a significant degree of highly desirable spatial freedom between the primary and secondary coils. Yet based on the model for a tightly coupled system, this arrangement should lead to very low efficiency. And it does, unless the coils are highly resonant. With highly resonant coupling of the magnetic field between the primary and secondary coils, efficient power transfer can be achieved between the coils.

What is this magical thing called resonance? It's a principle in physics that's been known and studied for many years. The classic example of resonance is the opera singer that sings and holds a specific musical note. Across the room are glasses filled to different levels to create "receivers" that will resonate at a particular frequency based on their physical characteristics set by the level of liquid in each glass. The glass that is resonant at the same frequency of the Opera singer's voice shatters due to the absorption of energy from the Opera singer's voice. Notice that in this example those glasses that did not resonate with the singer's voice did not absorb the same energy and did not shatter. In nature many objects have a natural resonant frequency based on their physical characteristics. In the electronics domain we can create a resonance with the proper selection of resistance, inductance and capacitance. Most electronics designers have unintentionally created a resonant circuit at some point in their career with unintended and disappointing results.

Figure 5: Nikola Tesla pictured with his tower used in loosely coupled resonant magnetic power experiments

Nikola Tesla demonstrated that the principle of resonance could be used for transferring power over the air back in the early 1900s[6]. Power by Proxi has been applying these principles to build loosely coupled systems for industrial markets with some success over the past few years. Solutions aimed at phones are being developed and demonstrated by companies, including MediaTek, Intel, Qualcomm and Power by Proxi, though no commercial products that have yet to be released.

In electrical systems, resonance is achieved by the appropriate design of a Resistance-Inductance-Capacitance (RLC) circuit. Resonance occurs at a particular frequency determined by the RLC values. The higher the Q (quality factor) of the circuit the higher the efficiency of energy transfer. The inductive reactance (ωL) and capacitive reactance ($-1/\omega C$) will be of equal magnitude at resonance where the Quality factor (Q) is then largely determined by the resistance in the circuit.

[6] http://en.wikipedia.org/wiki/Nikola_Tesla#Later_years_.281918-1943.29

$$\omega = \frac{1}{\sqrt{LC}}$$

ω=2πf where f is the frequency of resonance

We find it easier to achieve high Q at higher frequency and this is why you see so many developers of resonant systems operating at 6.78MHz. The WPC and PMA do not rely on high Q circuits and operate at lower frequencies (100s of kHz) where circuit design is simpler.

The theory behind highly resonant systems

Resonant systems are very similar to inductive systems in that there is a primary coil and secondary coil. The difference is that with loosely coupled resonant systems the secondary coil is not dependent on being in close proximity to a large percentage of the B field coming from the primary coil so long as high Q coils are used. In other words, effective power transfer is not strictly dependent upon alignment, size, shape or positioning of the secondary coil to the primary coil. In addition, and perhaps most importantly, multiple secondary coils can also be used to capture power since each coil can share the overall coupling with the primary coil and still have efficient power transfer according to the equation presented in the previous paragraph which graphically illustrates this principle. As shown, the charging of multiple devices, or 1:many charging, is inherently supported. People watching demonstrations often describe the loosely coupled systems as "magic" – but, of course, it's just cleverly applied physics.

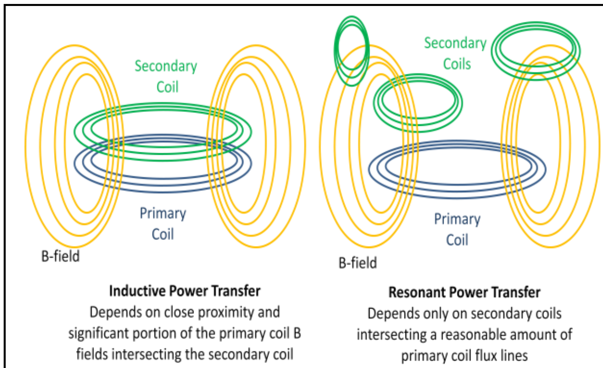

Figure 6: Inductive vs. resonant wireless power transfer

Summary on characteristics of loosely coupled highly resonant solutions

The physics of highly resonant, loosely coupled systems affords some unique properties that may enable the industry to deliver truly disruptive and compelling solutions to consumers. Resonant systems can ensure we can keep our many different portable electronic devices charged and ready for use at all times. **Resonance may be the key that drives early market adopters of inductive wireless charging to cross the chasm to the mass market and associated high volume purchases.**

Loosely coupled resonant wireless power solutions have the following key characteristics:

- Primary and secondary coils of different sizes
    - **Result:** Secondary receiver coils can be matched to the receiver device for optimal power.
    - **Result:** Secondary receiver coils can be matched to the device for mechanical fit (size and shape such as circle, square, rectangle, oval, etc.).
- Multiple devices can be charged on a single coil charger that enables 1:many charging
    - **Result:** One charger operating with a single coil under one standard can support charging of Bluetooth (BT) headsets, phones, cameras, tablets, etc.
- Devices can be placed on the charger pad in almost any orientation
    - **Result:** Almost any mechanical designs can be accommodated. For example, with BT headsets, you can simply place the headset onto the charging pad, rather than placing into a charging cradle that aligns to the planer charging surface.

The contrast between loosely and tightly inductive solutions is pretty dramatic. But the comparisons thus far are not complete. We need to also look at efficiency and cost.

The efficiency of loosely coupled resonant systems

Efficiency is an important consideration for wireless power. One can always deliver the target power almost regardless of the efficiency, but at what cost and size? The greater the efficiency the smaller the size and cost of the charger for the same delivered power. In the case of a smartphone the wired power has around 97 percent efficiency as measured from the wall socket to the 5V output to the battery. Wireless power efficiency will be less efficient. How much less depends on many factors including how large of a distance we want to charge over. Many people have the pre-conceived notion that loosely coupled resonant systems are lower efficiency than tightly coupled inductive systems. This is not the case. When comparing the two approaches on an equivalent basis resonance will have a slightly higher coil to coil efficiency. As the distance between the primary and secondary coils increases the efficiency of either system will decrease, but the decrease is much slower with loosely coupled resonant

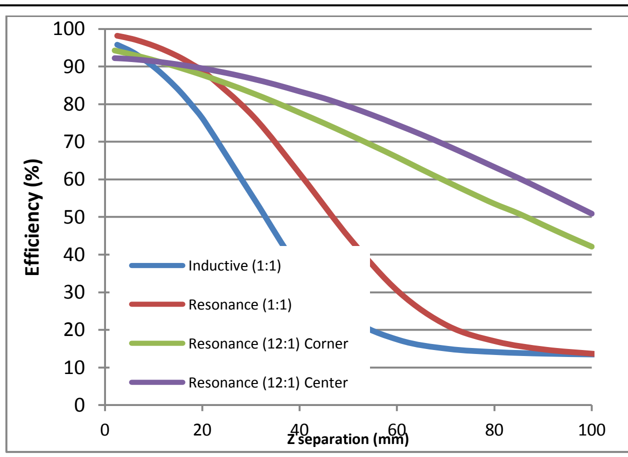

Figure 7: Efficiency comparison of simulated tightly coupled inductive and loosely coupled resonant coil to coil systems (see footnote for absolute coil sizes)

systems thus providing a significant advantage over inductive systems. This can easily be seen in Figure7[7] where the coils sizes are the same (1:1). However the really big advantage in efficiency for resonant systems comes when you have primary and secondary coils of different sizes such that you can support multiple receivers from a single primary coil. To charge three phones concurrently you might have a single primary coil in the charger that is 12 times larger than each of the three secondary receiver coils in the phones. The efficiency of a loosely coupled resonant system in this example is also shown in Figure 7 (12:1). Tightly coupled systems cannot operate in these conditions and therefore no data is presented. We can see from the curves presented that the optimal coil efficiency is always obtained when the primary and secondary coils are of the same size and positioned very closely together.

Around the coils you have the usual electronics that include a regulator, driver and matching network in the charger and a matching network, rectifier and regulator on the receiver side for both the resonant and inductive systems. The resonant system requires a buck regulator in the receiver section where some inductive solutions employ an LDO. The LDO has a slight advantage in efficiency as compared to the buck regulator. The inductive systems can use LDOs because the input voltages are well controlled since the receiver is always and necessarily in a 1:1 charging condition with tight coupling between the two coils. Resonant systems have a wide range of voltages presented to the regulator because of the varying coupling levels associated with spatial freedom and number of potential receivers in the field.

Cost comparison of loosely coupled resonant and tightly coupled systems

As already described, loosely and tightly coupled systems are quite similar in design. They will also be quite similar in cost and size. Both systems include the following blocks on the receiver side:

- Coil (PCB or Lizt)
- Ferrite
- Rectifier (often synchronous)
- Regulator
- Digital Processing

As mentioned the regulator in the resonant system is likely to be a buck regulator which requires the use of an inductor sized to the power requirements of the circuit. This inductor represents a slight increase in cost and size of implementation compared to an LDO based regulator.

[7] **Based on simulation data (in mms) using 1:1 coils that are 35x35:35x35 and 12:1 coils that are 171x130:54x36.**

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Communication between charger and receiver

For resonant systems the communication architecture may become a strong differentiator between competing systems. It is widely accepted that a wireless power system requires some communication between chargers and receivers to ensure a good user experience. Communications can be used to adjust for optimum source power level, distinguish between valid devices and foreign objects, and indicate fault conditions, to give a few examples. One-way communication from receiver to charger can offer most of these benefits, but two-way communications makes for more efficient use of the channel. With today's tightly coupled charging systems these communications are done "in-band". This means they use the same magnetic field required to transfer power as the carrier for communications (usually small changes in amplitude), much like RFID tags. The alternative would be to use a separate short range radio technology to communicate "out-of-band". The benefit of the in-band approach is that there is minimal cost and space required in the system to support communication. In addition, the system is inherently reliable, stable and free from external influence from other chargers. Communication only occurs when power is transferred from the charger to the receiver. In-band has another benefit for consumer devices in that dead battery conditions are inherently supported in the architecture because the system is self-powered.

Some suppliers of resonant systems will undoubtedly try to bring in-band architectures to resonance. However, implementing in-band solutions within loosely coupled systems is a difficult engineering problem due to the less predictable coupling levels between chargers and receivers. Any solution will require clever circuit design to create a well behaved system and advanced communication algorithms to pull a very small signal from a lot of system noise. The A4WP (loosely coupled solution) has publicly announced their adoption of an out-of-band communications architecture based on Bluetooth Low Energy (BTLE). This approach has the benefit of being an easier engineering problem to solve compared to in-band implementation, but unfortunately includes the higher cost and board area associated with BTLE transceivers at both the charger and receiver. You could save the cost of the BTLE in the receiver if you used the BT radio already present in the device (e.g. phone or tablet), but this is more complicated for the device design for a few reasons:

1. A data path must be established between the wireless power receiver and the Bluetooth (BT) radio on the phone (requiring one more set of interconnects and software overhead tasks).
2. The phone OS must take responsibility for communications associated with power control.
3. Dead batteries are not supported unless a dedicated power line is brought in from the wireless power receiver to the on-board BT solution. Power management systems today are not designed for this approach.

Compare these complexities with implementation of an in-band solution where the outputs of the wireless power receiver are V+ and Ground – that's it.

At a system level there are also concerns with chargers using out-of-band architectures interfering with each other. Chargers using BT have been shown to indiscriminately communicate with receivers associated with other chargers. This situation can lead to both operation and safety concerns. Chargers that use in-band architectures only communicate with receivers that they are actively associated with for charging.

One of the main challenges associated with adopting in-band architectures for loosely coupled systems has to do with the expected variation in coupling between the charger and the receiver. Inductive and resonant systems have comparable coupling and efficiency levels when the receiver is placed in the optimal charging position. However, resonant systems allow movement of the receiver away from the charger while still charging, albeit with lower coupling and efficiency as shown in Figure 8. Variations in coupling can be managed with good communications systems design. However with decreasing coupling levels the communications, signals will become increasingly small and eventually get lost in the system noise. Therefore loosely coupled systems using in-band communications will need to define a point of minimal coupling beyond which the communications and thus charging will cease. This point should in most applications, such as phones and tablets, be well beyond that of minimally acceptable power transfer efficiency. Applications where very low power efficiency is less of a concern, such as AA batteries, mice, or keyboards, might be served better with no communications (open looped power transfer) or out-of-band communications.

In summary, loosely coupled systems that support in-band communications will have a clear competitive advantage over systems using out-of-band architectures if the technical problems can be adequately addressed. These advantages include:

- Lower cost
- Smaller PCB area (important in phones and wearable devices)
- Higher reliability (power and communications are integrated)
- Lower complexity (power and communications are all self-contained)

Multimode solutions

The best situation for consumers in markets like that for wireless power is to have a single global standard specification so that all receiver and chargers are interoperable. But new industries don't often develop that way and wireless power is no exception. As previously mentioned, Powermat came to market first. Various suppliers launched products under the WPC specification some time later. But products based on each specification do not work with each other. If you buy a Powermat enabled phone you cannot charge it on a Qi certified charger. However industry suppliers like TI and IDT have developed dual-mode solutions where in this example a phone using a TI dual-mode receiver can charge from either a Qi or Powermat certified charger. With TI's solution there is no significant cost penalty for this feature in terms of bill of materials and size. So dual-mode solutions can be a great way to increase consumer convenience at low cost. Since the wireless charging market is not yet rallying around a single specification or standard we believe that the trend towards availability of dual-mode solutions is positive for the market.

When loosely coupled systems are introduced to the market in the coming months they will be incompatible with existing tightly coupled products. Can the principle of dual-mode be extended to multi-mode where a phone or tablet can charge from either a loosely or tightly coupled charger? Certainly the answer is technically yes, but at what cost? Can the multi-mode function be realized without significantly increasing the cost of the coil structure or the bill of materials? We think yes. Any such system will have to make sure that both the tightly and loosely coupled modes will provide for:

- Quick charging start times irrespective of charger specifications
- Low cost
- Small size
- Consistent, efficient power transfer

The complications of developing such a multi-mode system are beyond the scope of this article, but suppliers who can meet these targets will likely find strong market acceptance for their solution. In fact, low-cost, multi-mode solutions that protect the investments made in today's inductive charger infrastructure while offering the advantages of resonant charging may be critical in the market transition from early adoption (mostly inductive based) to early majority (mostly resonance based) phase.

Summary

Today's wireless charging systems have shown success in the market place with early adopters. These early adopters are consumers who want the latest and greatest technology, especially technology with a "wow" factor, almost regardless of price and convenience. The road is littered with failed products that do not make the jump from the early to mass market adoption phase. In following Geoffrey Moore's advice on how successful products cross the chasm to mass market success we look for truly innovative and disruptive technology that drive costs down and convenience up – disruptive technology that changes the way we charge consumer devices, such that it is seamless and available at costs palatable for high volume consumer markets.

Today's tightly coupled inductive wireless charging solutions are underwhelming to people more interested in the product (the mass market) than the technology (early adopters). Qi and PMA products users must still think about and plan for the charging of their devices, and do so at significant cost, given the need to purchase individual chargers for each device for concurrent charging and support of different classes of device (e.g. Bluetooth headsets, phones, tablets). Although inductive systems will undoubtedly continue to improve in performance and function, the physics that underlie the technology may prevent these products from ever improving enough to reach the high volume mass market adoption stage despite the significant marketing dollars being spent.

But if the techniques of loosely coupled highly resonant systems are applied to wireless charging we can see a path to a truly disruptive charging experience for consumers. The resonant technology will allow for a low cost, low complexity system with a single coil on the charger and receiver to:

- Charge multiple devices concurrently
- Charge different devices with vastly different power needs
- Charge different devices with vastly different form factors without coil-to-coil alignment
- Charge devices with easy, imprecise placement of the device on or near the charger
- Charge devices across distances and through furniture or even walls

The two major inductive consortiums, the WPC and the PMA, have recently recognized the importance of resonance. Each consortium is welcoming new members and new roles presumably to add resonance capability alongside their inductive technologies. MediaTek has joined the PMA as co-vice chairman of their new resonance technology working group. PowerbyProxi has joined the WPC and may lend their approach on resonance to the organization. MediaTek is already a member of the WPC and can be expected to also support the development of resonance within the WPC. Intel has recently thrown its weight into A4WP as a board member. Qualcomm has joined both the WPC and PMA groups. All major wireless power players are investing in resonant technology for the future.

Resonant charging systems are in their infancy and may have some early growing pains. But the benefits afforded by the underlying physics of this technology will be help bring the early success of inductive wireless charging across the chasm to mass market adoption.