ABSTRACT This study demonstrates tunable coil links for a wireless power transfer system with arbitrarily-located multiple receivers and arbitrary power division between them. Both the Tx and Rx coils are composed of a main coil and an array of assistant coils loaded with varactors. By tuning the varactors to control the resonant characteristics of each assistant coil, the Tx coil can steer the near field, and the Rx coil can reconfigure its electrical size. Consequently, the proposed system maintains the high overall efficiency regardless of the position of the receivers and the power division ratio. For the verification, a two-receiver system at 6.78 MHz is designed and fabricated with a $2 \times 1$ assistant coil array. A thorough investigation is performed for various cases, which include when the two receivers of the same size are located symmetrically with respect to the center of the Tx coil and two receivers of different sizes, located asymmetrically. For all cases, the overall efficiency is evaluated for various receiver locations and power division ratios when the tunable coil links are adopted on both Tx and Rx coils, only on either Tx or Rx coil. The conventional system provides the minimum transfer efficiency of 0% for symmetric case, as well as 12.8% for asymmetric case with respect to the receiver locations. On the other hand, results of the proposed system show minimum efficiency of 83.7% and 83.5% for symmetric and asymmetric case, respectively. More importantly, while the conventional system showed strong dependence not only on the Rx locations but also the power division ratio, the proposed system maintains the efficiency with little, if any, variation regardless of the two. For example, while the power division ratio is varied from 5:1 to 1:5, the proposed system remains a very high efficiency of up to 91.0% with only 0.3% variation.

INDEX TERMS Wireless power transfer, multiple receivers, tunable coil links, transfer efficiency, free positioning, arbitrary power division.

I. INTRODUCTION A wireless charger is an essential part of recent electronic applications owing to its outstanding convenience for use. Nonradiative wireless power transfer (WPT) systems based on inductive coupling have already been developed, and wireless chargers in the commercial market provide fast charging for smartphones. A magnetically coupled resonant WPT system is another nonradiative WPT system that can provide high transfer efficiency up to the mid-range [1], [2], [3]. However, a major disadvantage is that the transfer efficiency deteriorates significantly with lateral offset between the Tx and the Rx coils. Therefore, many WPT systems have been proposed that utilize a number of Tx coils [4], [5], sub-coils [6], [7], [8], resonator arrays [9], and 3D coils [10] to successfully compensate the degraded transfer efficiency due to misalignment.

When multiple devices are simultaneously charged wirelessly, lateral offset becomes even more critical since it may occur more frequently than in a single device charger. To this...
end, various techniques for planar WPT systems with multiple receivers have been proposed; these include use of rail transformers [11], switchable matching networks [12], and hybrid winding structures [13]. Although these have demonstrated a high total transfer efficiency up to 93% [12], the freedom in the location of Rx coils is relatively limited. A WPT system with stacked Rx coils [14] has been reported to avoid offset successfully; however, it suffers from not only different coupling coefficients but also interference among the Rxs, which makes the difference between transferred power of receivers as much as more 4 times.

Another issue for a multiple-receiver WPT system is the power division between each Rx for optimal charging. For example, tablet PCs have a considerably higher battery capacity than smartphones, and they may require more power to charge quickly. Further, even when two identical devices are charged simultaneously, the transferred power needs to be modified based on the amount of residual battery in each device. In this case, a WPT system is required where the coupling coefficient of different devices can be controlled adaptively. However, the coupling coefficient is determined mostly by the size and position of the Rx, i.e., the largest amount of power is transferred to the closest and/or largest Rx. In this case, techniques such as selective loading [15], [16] or impedance matching [17], [18], [19] must be employed to control the transferred power ratio among the Rxs. However, they require different frequency bands for each Rx, or the power division ratio between different Rxs is limited. Otherwise, the system must sacrifice the overall efficiency to achieve power division.

This work demonstrates tunable coil links for a multiple-device WPT system that maintains a very high overall transfer efficiency regardless of the location of the Rxs. Moreover, the efficiency remains not only high, but also virtually constant, regardless of the power division ratio between the receivers, even with different sizes. It can be achieved with tunable coil-link system which comprises a main (driving or load) coil and an assistant coil array, whose physical size is the same as that of the main coil. Each assistant coil in the array is loaded with a variable capacitor; controlling the resonant characteristic of each assistant coil expands the freedom in the positions of the multiple Rxs, as well as the range of power division ratio between them, which are the two most essential requirements in a multiple-receiver WPT system.

Although the WPT system with tunable Tx and Rx coil links provides the best performance, the asymmetric tunable coil-link WPT system that adopts tunable coil links at either Tx or Rx also provides outstanding performance. Further, the tunable coil links can be applied even if the Rxs have different size and/or are located asymmetrically. Hence, the proposed tunable coil-link system can solve the limitations of multiple-receiver WPT systems with practical planar structures.

The rest of this manuscript is organized as follows. In Section II, the configuration and analysis of the proposed system are presented. The effects of a tunable coil links with arbitrary positions of Rxs and an arbitrary power division to Rxs are investigated in Sections III and IV, respectively. Section V provides the experimental results for the tunable coil links. Two types of two-receiver systems are investigated; first is the system with two Rxs of the same size that are located symmetrically with respect to the center of the Tx coil. The second is with two Rxs of different sizes, located asymmetrically with respect to the center of the Tx coil. For both systems, the performance is evaluated for various Rx locations and power division ratios. Finally, for all cases, the effect of tunable coil-link system is analyzed not only when it is applied to both Tx and Rx coils, but also when it is adopted to Tx coil and to Rx coils.

II. PROPOSED TUNABLE COIL-LINK SYSTEM

Figure 1 shows the proposed tunable coil-link WPT system with multiple receivers. For simplicity, the number of receivers is set to two. The tunable coil links are composed of one main coil and an array of assistant coils; a driving coil (Tx) and assistant coils (Tx, i = 1, 2) in the Tx coil, a load coil (Rx) and assistant coils (Rx, i = 1, 2) in the Rx coil. Since the main coil and the assistant coils can be printed on both sides of a substrate for planar-type coils, the increase in the volume is minimized. For the Tx coil, only the driving coil is driven and for the Rx coil, only the load coil is connected directly with the load.

Each assistant coil in both Rx and Tx coils is loaded with a varactor to control its resonant characteristics. However, its effect is different for the two. For the Rx coil, the varactors

FIGURE 1. Side view of proposed tunable coil-link WPT system with two receiving coils.

FIGURE 2. Reconfiguring electrical size with assistant coils on Rx. (a) When both assistant coils are turned on and (b) When Rx is turned off.
are tuned to control the magnitude of the current flow in the assistant coil such that the effective electrical size of the coil is controlled to maximize the flux passing through. For instance, when the magnetic flux passing through a receiver coil is uniform, then the varactors can be tuned such that all assistant coils resonate at the same frequency as the flux from the Tx. Then the effective size of the Rx coil becomes the same as the load coil and the amount of flux passing through is maximized. However, the location of the Rx coil may be such that the flux passing through a certain part of the coil is in the opposite direction of the that passing through the other part. This results in reduced net amount of flux through the coil, resulting in degradation of the transfer efficiency. However, in the proposed system, the current flow in the assistant coils can be controlled with the varactors such that certain parts of the Rx coil receive little or no flux. Therefore, the effective amount of flux passing through the Rx coil, and therefore the transfer efficiency can be maximized, regardless of the position of the Rx coil with respect to the Tx coil.

This is illustrated in Fig. 2. In Fig. 2(a), the directions of the flux passing through the two assistant coils in the normal direction are opposite. When the location of the Rx coil is such that the amount of flux passing through the two in the normal direction are the same, then the net amount of flux through the Rx coil vanishes, resulting in a transfer null [20]. However, when the varactor on the assistant coil Rx\textsuperscript{a1} is controlled such that the coil is turned off, i.e. its resonant frequency is tuned far away from the operating frequency, then the effective size of the Rx coil is reduced to half as shown in Fig. 2(b). Despite the smaller size, this effectively increases the amount of magnetic flux passing through since the flux exiting in the opposite direction is no longer effective. Therefore, in a multiple-receiver WPT system, the tunable coil links applied to the Rx coil allows arbitrarily-positioned receivers to maintain high overall transfer efficiency.

On the other hand, the varactors that load each assistant coil in the Tx coil are tuned to control the magnitude of the current flow in the assistant coil, induced by the coupling from the driving coil. Since each assistant coil can be controlled independently, a simultaneous wireless power transfer to multiple receivers is possible. Further, the varactors can be tuned so that the amount of magnetic flux generated in each WPT region divided by each assistant coil can receive different amount of power. Thus, receivers in a different WPT region can receive different amount of power. Suppose that one receiver requires more power than the other in a two-receiver system. Then the varactors can be tuned such that more flux is generated towards this receiver than the other, i.e. the Tx coil is steered such that more power is transferred to one receiver than the other.

This is illustrated in Fig. 3. In Fig. 3(a), the two varactors in the two assistant coils are such that the currents induced on both coils are identical. In this case, the same amount of power is transferred wirelessly in the two regions divided by the two assistant coils. However, when the varactors are tuned such that the current on Tx\textsuperscript{a1} is much stronger than Tx\textsuperscript{a2}, i.e. the resonant frequency of Tx\textsuperscript{a1} is close to that of the driven signal while that of Tx\textsuperscript{a2} is far away from the operating frequency, then a much larger amount of power will be transferred in the left region than in the right, i.e. the Tx coil will steer the power more to the left. Therefore, in a multiple-receiver WPT system, the tunable coil links applied to the Tx coil allows to steer the radiated power to maintain high overall efficiency regardless of the power division ratio between the multiple receivers.

In this work, the assistant coil array in the Tx coil is in a 2 \times 1 configuration. Thus the freedom of receiver positions is only along the x axis. Further, the receivers are located in the two WPT regions divided by the 2 \times 1 assistant coil array in the Tx, i.e. one in the +x side and the other on the −x side. By increasing the size of the array, freedom in the location of the receivers and/or the number of receivers for simultaneous wireless power transfer can be increased. For example, increasing the size of the assistant coil array in the 2 \times 2 configuration allows the Rx coils to have position freedom in both x and y directions.

The assistant coil array in the Rx coil is also in a 2 \times 1 configuration. Therefore, the effective width of the coil can be controlled along the x direction only. Similarly, by increasing the array size to 2 \times 2, both the width and length of the coil can be controlled, at the cost of reduced Q and increased system complexity.

For verification of the proposed tunable coil-link system, the coils in Table 1 are designed and fabricated by printing the driving and assistant coils on both sides of a 1.5-mm-thick
substrate (RF-35 from Taconic). Therefore, the increase in the volume of the coil attributed to the increase in the number of layers caused by adding an assistant coil array is minimized. The schematic of the fabricated coils are shown in Fig. 4. Two different Rx coils are designed so that the performance of the proposed system can be verified not only for a symmetric system where the two Rx coils are identical, but also for an asymmetric system where the two Rx coils have different sizes. Moreover, as indicated in Table 1, the line widths, gap, and the number of turns for the two Rx coils are designed so that the total inductances are similar. This is to make the coupling coefficient is virtually the only determining factor for the transfer efficiencies for the two Rx coils in the asymmetric system for a simpler analysis. Finally, a larger number of turns (N) is considered for the Rx coils compared with that for the Tx coils to compensate for the smaller inductance caused by the smaller sizes.

### III. TWO-RECEIVER WPT SYSTEM WITH ARBITRARILY POSITIONED RECEIVERS

The proposed tunable coil-links system is an extremely versatile system that maximizes the total transfer efficiency in a multiple-receiver WPT system where the electromagnetic power from a single Tx is transferred wirelessly to multiple Rxs simultaneously, regardless of the locations of the receivers and the power division ratios.

The performance of the proposed system is investigated at 6.78 MHz for two cases. (a) A symmetric case, in which the two receivers of the same coil size are located symmetrically with respect to the center of the Tx coil. (b) An asymmetric case, which contains the Rx coils of different sizes located asymmetrically with respect to the center of the Tx coil. In all cases, the vertical distance of $D_z = 20 \text{ mm}$ between the Tx and the Rx coils was maintained.

The total transfer efficiency $\eta$ is the sum of the transfer efficiencies $\eta_i$, i.e., the transfer efficiency between the Tx$^D$ and Rx$^i$ coils ($i = 1, 2$). Here, the $S$-parameters are utilized as an indicator of transfer efficiency [10], [17], [21]. Thus for a two-receiver system, the total transfer efficiency $\eta$ is

$$\eta = \eta_1 + \eta_2 = |S_{21}|^2 + |S_{31}|^2,$$  

where $S_{i+1,i}$ denotes the $S$-parameter between the Tx$^D$ and Rx$^i$ coil. In this section, the varactors on the assistant coils on both the Tx and Rx sides are tuned so that the power division ratio between the two Rx coils is 1:1, i.e., $|S_{21}|^2 = |S_{31}|^2$ for all cases. This is so that the effectiveness of the proposed tunable coil links are verified from the location-free perspective only. Finally, all simulated results are obtained by post-processing the full-wave simulated results from ANSYS HFSS [22]. The driving and load coils are adaptively matched to provide a constant input power to the Tx coil regardless of the location of Rx coils [23].

The proposed coil system is a multi-coil system where cross coupling between coils may have non-negligible effect on the overall performance. Therefore, cross coupling is taken into account in all simulations throughout the manuscript.

### A. SYMMETRIC CASE

In the symmetric case, two RxA coils of the same size $100 \times 100 \text{ mm}^2$ are located symmetrically with respect to the center of the Tx coil, i.e., $\Delta D_x = 0$ in Fig. 1. The offset is set to $D_x = 50 \text{ mm}$ initially, and is increased up to 155 mm, where the Rx coils fall completely outside the Tx coil. The varactor on each assistant coil on both the Tx and Rx sides are tuned so that the total transfer efficiency $\eta$ is maximized while maintaining $|S_{21}|^2 = |S_{31}|^2$.

Figure 5 shows the simulated $\eta$ of the proposed tunable coil-link system at 6.78 MHz. For comparison, the total transfer efficiency $\eta$ of the conventional system composed of only main coils is also shown. When the two coils are located closely, i.e., when $D_x$ is small, both systems show virtually the same performance with a very high $\eta$. For instance, when $D_x = 55 \text{ mm}$, the simulated total transfer efficiencies are 97.9% and 98.3% for the proposed and the conventional systems, respectively. However, as $D_x$ increases, a dramatic decrease in the total efficiency is observed for the conventional system, which eventually reaches a transfer null at $D_x = 109 \text{ mm}$. This is when the two coils are located such that the net amount of magnetic flux passing through both coils in the normal direction vanishes. Therefore, coupling vanishes between the Tx and Rx coils, which results in zero transfer efficiency. On the contrary, the proposed tunable coil-link...
Table 2. Summary of loaded capacitances on assistant coils in symmetric WPT system for various offset.

| Assistant coil | 55 mm  | 109 mm | 135 mm |
|---------------|--------|--------|--------|
| Tx⁺⁺⁺⁺ | 120 pF | 150 pF | 130 pF |
| Tx⁺⁺⁻⁻ | 120 pF | 150 pF | 130 pF |
| Rx⁻⁻⁻⁻ | 100 pF | 80 pF  | 110 pF |
| Rx⁻⁻⁺⁺ | 100 pF | 230 pF | 110 pF |

The system does not suffer from such a transfer null. The total efficiency η remains high in the simulated range of Dx, with a minimum efficiency of 86.7% when Dx = 119 mm.

Since it is a symmetric system, i.e. identical Rxs located symmetrically with respect to the center of the Tx coil, the two varactors for the two assistant coils in the Tx coil have the same values for equal division of the transferred power. Further, at Dx = 55 mm, virtually all magnetic flux passing through the two assistant coils on the Rx side are in the same direction. Therefore, the varactors must be such that the effective area of the Rx coil is the largest, i.e. same as the load coil. This is verified by the two same 100 pF capacitances in Table 2, and the transfer efficiency that is virtually the same as the conventional system. A similar phenomenon is observed at Dx = 135 mm. The two varactors in an Rx coil are set to have the same value, and the proposed system shows a total transfer efficiency of 91.1%, which is practically the same as the total efficiency of 92.9% for the conventional system. All four capacitances increased slightly from Dx = 55 to 135 mm, which is to compensate the reduced coupling, i.e. to compensate the reduced mutual inductance at Dx = 135 mm with a higher capacitance to maintain the same resonant frequency.

At Dx = 109 mm, the amount of magnetic flux passing through the Rx coil in the +z direction and –z direction is the same, resulting in net zero magnetic flux. In this case, the two varactors in the Rx coil are tuned such that the effective area of the Rx coil is reduced to half. As explained by Fig. 2, this effectively maximizes the net amount of magnetic flux passing through. This is achieved by maintaining the resonant frequency of one assistant coil at 6.78 MHz, while moving that of the other away from 6.78 MHz so that the coil operates as an open coil with no current flow.

B. ASYMMETRIC CASE

Figure 6 shows the total transfer efficiency η for the asymmetric case with respect to Dx, where two Rxs of different sizes are located asymmetrically along the center of the Tx coil. In this case, while the size of Rx #1 is still 100 × 100 mm² (Rx₁), that of Rx #2 is reduced to 70 × 70 mm² (Rx₂), which is about half of the larger one. Further, the additional offset is set to ΔDx = 20 mm, with Rx #1 in the –x side and Rx #2 in the +x side of the Tx coil. The two coils are set to receive the same amount of power, i.e. |S₂|² = S₁|². Again for comparison, the results for the conventional system is also provided.

Results for the conventional system show that it no longer suffers from transfer null as the symmetric case did. This is due to the asymmetry of the system: the two coils of different sizes cannot be located at the transfer null point simultaneously. However, it still suffers from transfer valleys, with substantially low overall efficiency. Moreover, there are two valleys in the simulated Dx range. The first valley appears at Dx = 82 mm. This is when Rx #2 is located at Dx + ΔDx = 102 mm, which is a transfer null point. Since Rx #2 cannot receive any power, Rx #1 must not receive any power either in order to receive the same power, i.e. to satisfy the condition |S₂|² = |S₁|². However, the simulated efficiency of 30.2% indicate that the two receivers are indeed receiving non-zero amount of power. This means that although Rx #2 is located at a transfer null point, it still receives power not from the Tx, but coupled from Rx #1.

A similar phenomenon occurs at Dx = 109 mm where Rx #1 is now located at the transfer null point. Nevertheless, the conventional system suffers from rapid decrease in the total transfer efficiency around the two points, which is as low as 13%. On the other hand, the assistant coils in both the Tx and Rx sides of the proposed system removes the transfer valleys to maintain a very flat total transfer efficiency above 86.6% in the entire simulated Dx range.

The values of all varactors for various offset Dx is summarized in Table 3. Since it is an asymmetric system with equal power division, the two varactors in the Tx coil require different values to steer the generated magnetic field and compensate for the difference in the size and location of the two Rxs. A larger current is induced in the assistant coil closer to the smaller coil to maintain the equal power division. At Dx = 55 mm, the assistant coil Tx₃₋₋ is open circuited, as indicated by the varactor capacitance of 0 pF. Since the larger Rx #1 have a larger coupling coefficient than the smaller Rx #2, the assistant coil Tx₃₋₋ which transfers power mostly to Rx #1 is turned off and Rx #1 receives power only from the driving coil which is misaligned so that the power division ratio of 1:1 is maintained.

Similar to the symmetric case, the varactors in the Rx coils are tuned such that the effect area of the Rx is adjusted to maximize the total flux passing through. This includes to open
the assistant coils with 0 pF, which is effectively the same as without the assistant coils. For instance at $D_x = 109$ mm, the Rx #1 is at the transfer null point. In the symmetric system, this was compensated by reducing the effective electrical area of Rx #1. However, in the asymmetric system, the operation is more complex.

First, in the asymmetric system, the varactors in the Rx #1 are tuned so that its effective area is adjusted to half. This maximizes the magnetic flux passing through, which would have resulted in net zero flux if not tuned. This is exactly the same as the symmetric system. At this point, the equal power division cannot be maintained since the two coils now have the same effective area, but Rx #2 is located further away from the center of the Tx coil than Rx #1 due to the extra offset of $\Delta D_x = 20$ mm. Therefore, the varactors in the Tx coil must be tuned so that the magnetic field is steered more in the direction of Rx #2. Finally, the two varactors in the Rx #2 are tuned adaptively to the steered Tx field so that equal power division is achieved.

### IV. TWO-RECEIVER SYSTEM WITH ARBITRARY POWER DIVISION RATIO

In the previous section, the ability of the proposed tunable coil links to maintain a high efficiency in a two-receiver WPT system with arbitrarily-located receivers, whether symmetric or asymmetric, is demonstrated for a power division ratio of 1:1, i.e. the two same-sized Rxs receiving the same amount of power. This section investigates the ability of the tunable coil links to maintain high efficiency in a two-receiver WPT system, regardless of the power division ratio $R$ between the two receivers, where

$$R = \eta_1 : \eta_2 = |S_{21}|^2 : |S_{31}|^2.$$  \hspace{1cm} (2)

#### A. SYMMETRIC CASE

Similar to the previous section, both the symmetric and asymmetric WPT systems are investigated. In the symmetric case, two coils with the size of $100 \times 100$ mm$^2$ are located such that $D_x = 108$ mm, which is immediately next to the transfer null, with a vertical distance $D_z = 20$ mm.

Figure 7 shows the simulated total transfer efficiencies for various power division ratio $R$, for a symmetric two-receiver system with coils of $100 \times 100$ mm$^2$ size, located symmetrically with respect to the center of the Tx coil with $D_x = 108$ mm and vertical distance $D_z = 20$ mm. Both the conventional and the proposed system shows the highest overall transfer efficiency when $R = 1:1$, where the coupling coefficient between the Tx and both Rxs is the same.

However, the total transfer efficiency for the conventional system is $\eta = 39.4\%$, which is substantially lower than that of the proposed system $\eta = 93.1\%$. Further, the situation becomes worse as the power division ratio $R$ is varied. As $R$ is tuned to 1:5, the conventional system suffers from a large 8.6% decrease in the overall transfer efficiency. This is because the conventional system achieves power division by adjusting the load impedances based on an impedance matching network [17], [18], [19]. Because of the intentional mismatch, lower efficiency is inevitable. On the other hand, the proposed system maintains virtually the same total transfer efficiency, without any sacrifice in the transfer efficiency regardless of the power division ratio.

The capacitance sets in Table 4 show important results. For $R = 1:1$, the two capacitances in the Tx coil are the same. This is to generate the same amount of magnetic flux in the two WPT regions. Further, the capacitance conditions for both Rxs are identical due to the equal power division. As $R$ is varied, the capacitances in the Tx coil must change to steer the near field according to the $R$. However, the capacitances remain the same in the Rxs, regardless of $R$, i.e. the optimal effective size of Rx to maximize $\eta$ does not change.

This clearly reveals the different roles of the tunable coil links in the Tx and Rx coils. Tuning of $R$ is achieved by the tunable coil links on Tx coil only, by moving the resonant frequency of the assistant coil closer to the Rx that receives

### TABLE 3. Summary of loaded capacitances on assistant coils in an asymmetric WPT system for various offsets.

| Assistant coil | 55 mm | 82 mm | 109 mm | 135 mm |
|----------------|-------|-------|--------|--------|
| $T_{x_1}$      | 0 pF  | 60 pF | 120 pF | 80 pF  |
| $T_{x_2}$      | 140 pF| 170 pF| 160 pF | 160 pF |
| $R_{x_1}$      | 0 pF  | 0 pF  | 80 pF  | 30 pF  |
| $R_{x_2}$      | 0 pF  | 0 pF  | 230 pF | 70 pF  |
| $R_{x_1}$      | 120 pF| 150 pF| 60 pF  | 120 pF |
| $R_{x_2}$      | 120 pF| 260 pF| 120 pF | 120 pF |

### TABLE 4. Summary of loaded capacitances on assistant coils in a symmetric WPT system for various power division ratios.

| Assistant coil | 1:1  | 1:3  | 1:5  |
|----------------|------|------|------|
| $T_{x_1}$      | 150 pF| 190 pF| 210 pF|
| $T_{x_2}$      | 150 pF| 130 pF| 120 pF|
| $R_{x_1}$      | 80 pF | 80 pF | 80 pF |
| $R_{x_2}$      | 230 pF| 230 pF| 230 pF|
| $R_{x_1}$      | 80 pF | 80 pF | 80 pF |
| $R_{x_2}$      | 230 pF| 230 pF| 230 pF|

**FIGURE 7.** Simulated total transfer efficiencies of symmetric WPT systems according to power division ratio with $D_x = 108$ mm.
Nevertheless, the overall efficiency is very low at 13% when receiving power from Tx, part of which is relayed to Rx #1. The smaller Rx #2, which is not located at the null, does not receive power from the Tx around \( D_x = 109 \) mm. Therefore, the overall transfer efficiency must be \( \eta \) for various power division ratios. Simulated total transfer efficiencies of asymmetric WPT systems according to power division ratio with \( D_x = 109 \) mm.

### TABLE 5. Summary of loaded capacitances on assistant coils in asymmetric WPT system for various power division ratios.

| Tunable coil links | 5:1 | 1:1 | 1:5 |
|--------------------|-----|-----|-----|
| \( T_{x_1} \) | 0 pF | 120 pF | 190 pF |
| \( T_{x_2} \) | 190 pF | 160 pF | 120 pF |
| \( R_{x_1} \) | 80 pF | 80 pF | 80 pF |
| \( R_{x_2} \) | 230 pF | 230 pF | 230 pF |
| \( R_{x_3} \) | 60 pF | 60 pF | 60 pF |
| \( R_{x_4} \) | 120 pF | 120 pF | 120 pF |

less flux away from 6.78 MHz, while the resonant frequency of the assistant coil closer to the Rx that receives more flux is maintained around 6.78 MHz. Although the results are shown only for one location, similar results are obtained for other locations. Therefore, the proposed tunable coil links maximize \( \eta \) regardless of \( R \).

### B. ASYMMETRIC CASE

Figure 8 shows the calculated total transfer efficiencies for various power division ratio \( R \), for an asymmetric two-receiver system with coils of 100 \( \times 100 \) mm\(^2\) and 70 \( \times 70 \) mm\(^2\) size for Rx #1 and Rx #2, respectively, located asymmetrically with respect to the center of the Tx coil with \( D_x = 109 \) mm and \( \Delta D_x = 20 \) mm. The vertical distance between Tx and Rx coils are maintained at \( D_y = 20 \) mm. Similar to the symmetric system, the conventional system suffers from a total transfer efficiency of 13% that is incomparable to that of 115.7% for the proposed system.

The conventional system shows a transfer valley at \( D_x = 109 \) mm. Since then Rx #1 is located at the transfer null, the overall transfer efficiency must be \( \eta = 0 \). However, the smaller Rx #2, which is not located at the null, does receive power from Tx, part of which is relayed to Rx #1. Nevertheless, the overall efficiency is very low at 13% when \( R = 1:1 \) due to the low efficiency of the power relay. As \( R \) is tuned by controlling the impedance matching such that Rx #2 receives more power than Rx #1 which is located at the transfer null, the efficiency increases. For instance for \( R = 1:5 \), the efficiency increases from 13% to 31.1%. This is because the low-efficient power relay from Rx #2 to Rx #1 is not required as much. On the other hand, when \( R \) is tuned such that the Rx #2 receives less power than the Rx #1, for instance \( R = 5:1 \), more power must be relayed from Rx #2 to Rx #1 since Rx #1 is located at the transfer null and cannot receive any power directly from the Tx coil. Therefore, the overall efficiency decreases even further to 8.3%, indicating that both coils are receiving little power although to achieve the power division ratio of 5:1.

On the other hand, the tunable coil links maintains a high efficiency, which remains relatively constant regardless of \( R \). As \( R \) changes from 5:1 to 1:5, \( \eta \) changes from 91.3% to 87.3%. In contrast to the conventional system, the overall efficiency is lower when Rx #2 receives more power than when Rx #1 receives more power, although the difference is small. This is natural because the Rx #2 is less efficient due to the smaller size. Further, the fractional variation in \( \eta \) that the proposed system exhibit as \( R \) varies from 5:1 to 1:5 is only 5.9%, which is incomparable to that of 115.7% for the conventional system. This indicates that besides showing a high overall \( \eta \), it is maintained regardless of \( R \).

The capacitance conditions for the asymmetric case are summarized in Table 5, which shows a very similar trend as the symmetric case: adjustment of \( R \) is achieved with the assistant coils in the Tx coil only.

### V. EXPERIMENTAL VERIFICATION OF THE PROPOSED TUNABLE COIL-LINK SYSTEM

For the experimental verification, the coils in Table 1 are fabricated on a 1.52-mm Taconic RF-35 (\( \epsilon_r = 3.5 \)) substrate. As shown in Fig. 9, an acrylic fixture was used to fix the vertical distance between the Tx and Rx coils at \( D_y = 20 \) mm and to position the Rx coils accurately.

To adjust the loaded capacitance on each assistant coil, Infineon BBY66 was used. A total of four different cases are measured; when the tunable coil links are adopted only on the Tx coil, only on the Rx coils, and on both the Tx coil and Rx coils. The last case is when the technique is not applied on any side, which is the conventional case. The S-parameters between the Tx and Rx coils were measured using a ZNB8 VNA from ROHDE & SCHWARZ, calibrated using a ZVZ135 kit. Measured S-parameters are post-processed using the Agilent Advanced Design System (ADS) to achieve optimal matching conditions for the 50-Ω system at 6.78 MHz.

Figure 10 shows the measured and simulated \( \eta \) with respect to the offset \( D_y \) when the Rxs are symmetrical with the power division ratio \( R = 1:1 \). For comparison, the measured results of a conventional counterpart are provided. Simulated results for all cases are also provided.

The measured total efficiency \( \eta \) of the conventional system starts to decrease sharply at approximately \( D_y = 105 \) mm, and it shows a transfer null at \( D_y = 109 \) mm. Therefore, the Rx coils cannot receive power from the Tx around \( D_y = 109 \) mm, although the Rxs are still located within the Tx. However, the WPT system with the proposed tunable coil links successfully
eliminate the transfer null. When the tunable coil links are adopted only on the Tx coil, it shows a local minimum with $\eta = 73.0\%$ at $D_x = 113$ mm. This is a 25.0% decrease from that at $D_x = 55$ mm, i.e. when the two Rxs are as close to each other as possible.

On the other hand, when the tunable coil links are adopted only on the Rx coils, the local minimum in the transfer efficiency of 85.8% occurs at $D_x = 121$ mm. Compared with the case when the tunable coil links are applied only on the Tx side, the location of the local minimum occurs at a slightly larger $D_x$, with a local minimum efficiency that is nearly 1.2 times higher.

Finally, when the tunable coil links are adopted on both the Tx and Rx coils, the local minimum in the transfer efficiency of 83.7% is measured at $D_x = 119$ mm. Considering the experimental errors, this is virtually the same as that when the tunable coil links are applied only on the Rx coils, which corresponds well with the simulated results that expected a difference of only 1.1% between the two. Thus, in the symmetric case with $R = 1:1$, the performance enhancement in $\eta$ is mostly due to the tunable coil links on the Rx coils, although tunable coil links only on the Tx coil are still beneficial. This is because when $R = 1:1$, the overall efficiency relies more on compensating the transfer null with the tunable coil links on the Rx side, rather than the steering of the power that is wirelessly transferred from the Tx coil.

The experimental total efficiency $\eta$ for the asymmetric case with $R = 1:1$ is shown in Fig. 11. The results reveal that although the conventional system shows a very high total efficiency of 95.9% at $D_x = 55$ mm, it suffers from two evident transfer valleys, the first one at $D_x = 82$ mm with $\eta = 30.0\%$ and the second one at $D_x = 109$ mm with $\eta = 13.0\%$. The former is due to the smaller coil Rx$_B$ that is located at the transfer null point, while the latter is because the larger coil Rx$_A$ is located at the transfer null point.

Again, when the tunable coil links are on both sides and when they are on the Rx coils show virtually the same performance, and maintains the total efficiency $\eta$ extremely flat above 82.0% in the entire range of $D_x$ tested. When tunable coil links are on the Tx coil only, the efficiency is somewhat lower than the previous two cases. However, this is only around the valleys of the conventional system, and still shows great compensation of the total efficiency that is higher than 75.4% in the entire range. As was the case for the symmetric system, the assistant coils on the Rx coils play the dominant role in the two-receiver asymmetric system with $R = 1:1$.

Figure 12 shows the simulated and measured results of $\eta$ according to the $R$ for the symmetric case, when two identical

| $D_x$ (mm) | Conv. | Proposed with tunable coil links on |
|-----------|-------|----------------------------------|
|           |       | Tx | Rx | Both |
| Sym.      |       |     |     |      |
| $D_x=55$  | 97.3% | 97.3% | 96.8% | 97.3% |
| Local min. | 0%   | 73.0% | 85.8% | 83.7% |
| (@ $D_x$) | (109 mm) | (113 mm) | (121 mm) | (119 mm) |
| Degradation | 100% | 25.0% | 11.4% | 14.0% |
| Asym      |       |     |     |      |
| $D_x=55$  | 95.9% | 96.6% | 93.4% | 94.3% |
| 1st Local min. | 30.0% | 75.4% | 82.7% | 83.5% |
| (@ $D_x$) | (82 mm) | (88 mm) | (92 mm) | (95 mm) |
| Degradation | 68.7% | 22.0% | 11.5% | 11.5% |
| 2nd Local min. | 12.8% | 82.4% | 85.1% | 83.5% |
| (@ $D_x$) | (109 mm) | (116 mm) | (121 mm) | (123 mm) |
| Degradation | 86.4% | 14.7% | 8.9% | 11.5% |
Rx coils with 100 × 100 mm² sizes are located symmetrically at $D_x$ = 108 mm, which is immediately next to the transfer null. The conventional system suffers from $\eta$ that is only 40.3% when $R = 1:1$, which reduces to 35.0% when $R$ is tuned to 5:1. However, the proposed system increases the efficiency dramatically, and minimizes the degradation due to unequal power division.

As $R$ is tuned, the role of the tunable coil links on the Tx coil becomes more important because they can steer the generated flux from the Tx coil. Thus, the cases when tunable coil links are on both Tx and Rx coils show higher efficiency than when the tunable coil links are on Rx coils only. Nevertheless, the case when tunable coil links are on the Tx side only still shows significant enhancement in the total efficiency, and maintains it relatively flat regardless of the power division ratio.

Figure 13 shows the total efficiency $\eta$ with respect to $R$, when two Rxs with different sizes in Table 1 are located asymmetrically with $D_x$ = 109 mm and $\Delta D_x$ = 20 mm. This is the case when the larger Rx coil (Rx$_A$) is located at a transfer null point. Again, the conventional system suffers from substantial deterioration in the overall efficiency that is as low as 7.9% when $R = 5:1$. Although the efficiency increases as $R$ is tuned, it is still very low at 30.3% when $R = 1:5$. On the other hand, the tunable coil links, whether on the Rx side only, Tx, side only, or on both sides, shows remarkably high total efficiency with insignificant degradation in $\eta$ due to tuning of $R$. For all cases, the $R = 5:1$ case shows slightly higher efficiency than the $R = 1:5$ case, since the steering of Tx is more efficient when more power needs to be delivered to the larger coil, than to the smaller, as discussed at the end of Section IV. The measured results for the symmetric and asymmetric cases with respect to $R$ are summarized in Table 7.

Table 8 summarizes the recent state-of-the-art works on multiple-device WPT systems, which all show successful demonstration of wireless power transfer technology to multiple receivers with different power division. For example, the time-division management technique [16] can provide an unlimited power division ratio. However, the freedom in the location of the receivers is limited in most cases. This can be overcome using repeaters [18], at the cost of increased system complexity and reduced versatility.

On the other hand, the proposed WPT system maximizes the freedom in the location of multiple receivers to allow high efficiency even when the Rx coils fall completely outside the Tx coil. Further, a very high transfer efficiency is maintained with minimal variation even when the power division ratio is tuned for Rx coils with different sizes. Moreover, even when the tunable coil links adopted on either side, the performance degradation is not significant, revealing the versatility of the proposed system. Therefore, the proposed tunable coil links are expected to be a strong candidate to develop a practical multiple-device wireless charging system to provide a very high efficiency regardless of the positions of the receivers, the remaining battery capacity, and/or charging speed required.

The power capacity of the proposed system is dominated by the power handling capacity of the varactors. Although not shown in here, the performance degradation due to the non-ideal varactors is negligible for low to medium input
TABLE 8. Comparison of multiple-device WPT systems.

| Tx Size | Rx Size | Vertical Distance (cm) | Frequency (MHz) | Support | Total Transfer Efficiency (%) |
|---------|---------|------------------------|----------------|---------|-------------------------------|
|         |         |                        |                | Asymmetric Rx | Freedom in Rx Location | Power Division |                  |
| [12]    | φ18 cm  | φ4.7 cm                | 1.2            | 6.78     | Location only               | Within Tx     | 82~93              |
| [16]    | φ5.6 cm | φ1.2 cm                | 4.3            | Triple band | Fixed, Inside               | Possible      | 24~29              |
| [18]    | φ30 cm  | φ30 cm                 | 0 & 16         | 13.56    | Location only               | Outside Tx possible with repeaters | 73~87          |
| [24]    | 26×12 cm² | 12×12 cm²               | 3              | 6.78     | Size and location           | Within Tx     | 70.7~85.5†         |
| Prop.   | 20×20 cm² | 10×10 cm²               | 2              | 6.78     | Size and location           | Outside Tx possible | 83.7~97.3*         |

† denotes the system efficiency, and ∗ denotes symmetric case.

power levels, and is less than 0.6 dB up to +10 dBm of input power. The 1-dB compression point is 22 dBm for a lateral offset of $D_h = 55$ mm for the symmetric case and equal power division, which decreases as $D_h$ increases. In this work, general-purpose varactors are utilized. By replacing these with high-power varactors such as those in [25], the power capacity of the system can be increased. Various other methods are available, including the power dividing technique [26] and the switching network [27], that can be integrated to increase the power capacity.

VI. CONCLUSION

A tunable coil-link WPT system for multiple receivers was demonstrated. The tunable coil links are composed of a main coil and an array of assistant coils that are loaded with varactors. By tuning the resonant characteristics of each assistant coil with varactors, the Tx coil can steer the generated magnetic flux and the Rx can be reconfigured to have a different electrical size. Therefore, the proposed system maintains high efficiency, regardless of the positions and the receivers and power division ratio between them.

For the experimental verification, a two-receiver tunable coil-link system at 6.78 MHz is designed and fabricated with a 2 × 1 assistant coil array for all coils. Experimental results for various cases all reveal performance that is incomparable with the conventional counterpart, without any transfer nulls or valleys. For instance, when the two same-sized Rx coils that are located symmetrically, the proposed system shows a very high overall transfer efficiency of 97.3% for a power division ratio of 1:1, while the conventional system may suffer from a efficiency null where both receivers receive no power. The asymmetric configuration of the proposed system also shows great enhancement with a efficiency that is as much as 6.5 times higher than the conventional counterpart. Furthermore, with the proposed tunable coil links, a high transfer efficiency is maintained within a wide range of power division ratio between the Rx coils. As the power division ratio is tuned from 5:1 to 1:5, the system showed transfer efficiencies that is not only very high, but also that varied minimally between 83.7% to 91.7%, whose variation is 9.1%, for a two Rx coils with different size are located asymmetrically.

However, the efficiency of conventional system becomes as low as 7.9% with 117.3% variation. Based on a predetermined criteria, the proposed system is capable of allocating the power differentially to a number of devices, but still maintain the high efficiency. Verification of the proposed technique with an increased array size to accommodate a lager number of Rxs remains as a future work.

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