Master's Thesis
석사 학위논문

Exploiting mutual coupling in simultaneous wireless information and power transfer

Jun Hee Kim (김 준 희 金 俊 喜)

Department of Information and Communication Engineering
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Advisor : Professor Ji Hwan Choi
Co−Advisor : Professor Youn Gu Lee

by

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Department of Information and Communication Engineering
DGIST

A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of ICE. The study was conducted in accordance with Code of Research Ethics[1].

12. 30. 2015

Approved by

Professor Ji Hwan Choi (Signature)
(Advisor)

Professor Youn Gu Lee (Signature)
(Co−Advisor)

1) Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Exploiting mutual coupling in simultaneous wireless information and power transfer

Jun Hee Kim

Accepted in partial fulfillment of the requirements for the degree of Master of Science.

12. 30. 2015

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Abstract

Simultaneous wireless information and power transfer (SWIPT) is an essential technology for future Internet of Things (IoT) networks. In this paper, the mutual coupling effect for SWIPT is presented by conducting simulations. In terms of energy harvesting, when mutual coupling exists with the spacing of antennas near half wavelength, the total received power can be as much as 5.10 μW, 1.47 times larger than the value without mutual coupling, showing that the received power of the half wave dipole antenna can be increased by exploiting mutual coupling. In addition, based on theoretical analysis, we attempt to generalize the mutual coupling effect for more than two dipole antennas. Analytical results show that the received power gain with mutual coupling can be more than 50%, compared to the uncoupled case. In terms of channel capacity in single-input multiple-out systems, the channel capacity is fluctuating as the interval of antenna is changed. Also, our results shows that the channel capacity that the coupled and uncoupled case are converged because the impact of mutual coupling decrease as the spacing of antennas is larger.

Keywords : SWIPT, mutual coupling, mutual impedance, radio frequency (RF) energy harvesting, channel capacity in SIMO systems

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I. INTRODUCTION

1.1 Internet of Things

Internet of Things (IoT) means technology that trade the data between things in real time. Specifically, it allows physical things and objects around us to access to the internet and they can be communicated each other. IoT is expected to improve the quality of human life because it has a wide range of applications in industries. For example, in intelligent agriculture, sensors measure the rainfall and soil humidity to decide the quantity of fertilizer. In machine health monitoring, the collected data from wireless sensors are used for checking industrial facilities. Also it can be adapted in smart water systems which prevent the water leak by using sensors. However, because the battery capacity of sensor nodes is limited, users have to replace batteries frequently, which reduces the economic competitiveness of networks. One of the key technologies to solve the battery problem in sensor nodes is simultaneous wireless information and power transfer (SWIPT), the process of utilizing electromagnetic waves from the ambient environment.

1.2 Simultaneous wireless information and power transfer

In wireless communications, radio frequency (RF) signals are used as means of transportation for conveying information. Since RF signals are also electromagnetic waves, it can be a source for harvesting energy. SWIPT technology utilizes RF signals for energy harvesting and information decoding. SWIPT is a promising solution to solve the battery problem in energy constrained wireless networks [1]. Therefore, a lot of research has been studied in recent years [2]–[4]. Varshney suggested the idea of simultaneously transmitting information and power for the first time and the fundamental tradeoff between information and power transfer was studied in [2]. In [3], due to energy harvesting circuits from RF signals are not yet able to decode the information, the operation scheme and architecture design of receiver in SWIPT were discussed. Specifically, the operation scheme of receiver is divided into power splitting and time switching [3]. In the time switching method as shown in Fig. 1(a) the received RF signals are used for energy harvesting for the first time interval α and then used for information decoding for the remain time interval $(1-\alpha)$. The power splitting method is illustrated in Fig. 1(b). The received RF signals are splitted into two power streams with specific dividing ratio. Then two power streams flow into energy harvesting and information decoding respectively. Based on time switching operation, time-varying co-channel interference was utilized for SWIPT in [4]. The receiver is switched for energy harvesting when the interference is strong and it is switched for information decoding when the channel state is good. Therefore, a time switching receiver can optimize energy harvesting and information decoding when the channel state information is known at the receiver.

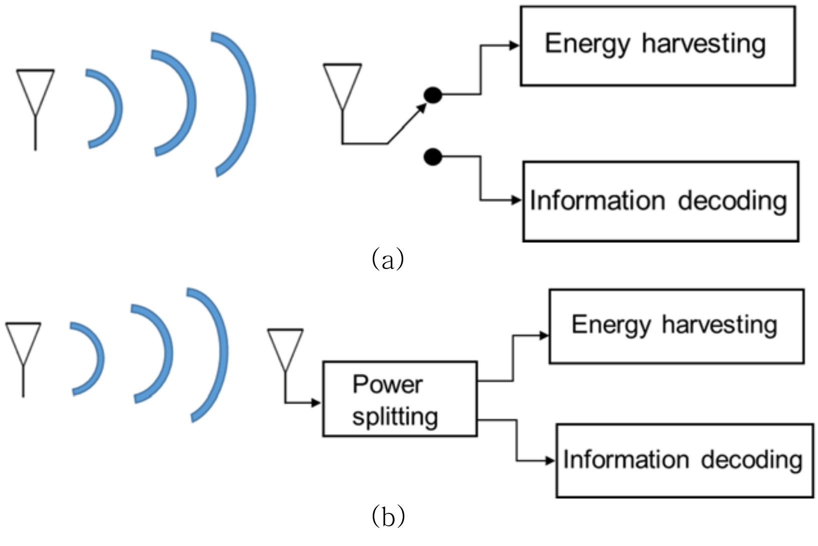


Fig. 1. Scheme of receiver operation in SWIPT (a) Time switching (b) Power splitting

Although SWIPT systems enable to utilize the RF signals a single antenna can not harvest the power to be used as a source of sensor nodes. e.g, the loop antenna can capture the RF power from 0.18 to 84 nW depending on the frequency and the spiral antenna can receive as much as 63 nW. In general, ultra-low power sensors need more than a few microwatts; e.g., the body motion sensor consumes 6.6 μW including hardware [5] and the temperature sensor requires 7.4 μW [6]. To increase the harvested power for the sensor nodes, an array of rectennas is required. When antennas are arranged, however, the coupling phenomena, called "mutual coupling", exist between antennas. Mutual coupling distorts current distributions on antennas and it affects the performance on energy harvesting and information decoding. Therefore, analyzing effect of the mutual coupling on SWIPT performance is required.

The rest of this paper is organized as follow: In section 2, we explain the mutual coupling on energy harvesting and information decoding. In section 4, optimization problem to maximize SWIPT performance is discussed. Finally, we conclude the effect of mutual coupling on SWIPT.

II. Mutual coupling

2.1 Mutual coupling effect

Mutual coupling effect is defined as the interaction of electromagnetic waves between antennas. When the antenna receives electromagnetic waves it would alter the current distribution adjacent antennas. Fig. 2 shows the process of occurring mutual coupling. It can be simplified 6 steps.

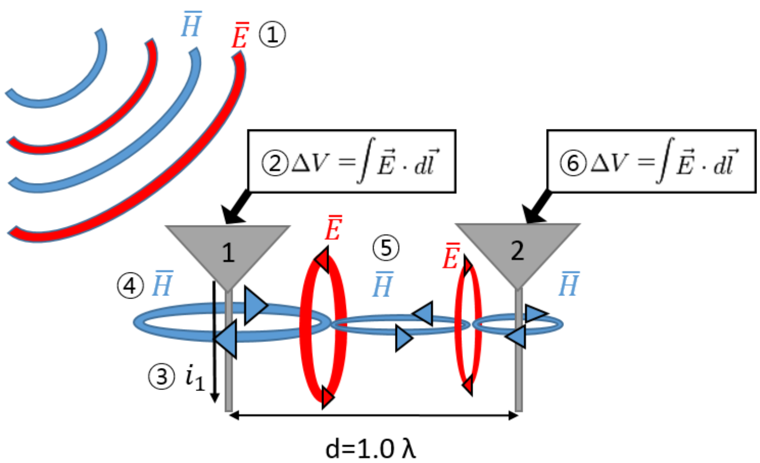


Fig. 2. Electromagnetic coupling between antennas.

1. The electromagnetic waves are incident in antenna 1.

2. The current flows on antenna 1 and the magnetic field is generated.

3. The electric field is generated from the magnetic field.

4. The magnetic field re−induces from electric field.

5. Step 3 and 4 are repeated until the electric field reaches other antennas.

6. When the electric field arrives antenna 2 it induces potential differential and it distorts current distributions on antenna 2.

In previous research, the mutual coupling between dipole antennas was analyzed by modeling mutual impedance [7]−[8]. In the case that antenna 1 has influence on antenna 2, as shown in Fig. 3, the mutual impedance is defined as the induced voltage divided by current:

$$Z_{21} = \frac{V_{2ind}}{I_1}, \tag{1}$$

where V_{2ind} is the induced voltage due to antenna 1 and I_1 is the current on antenna 1.

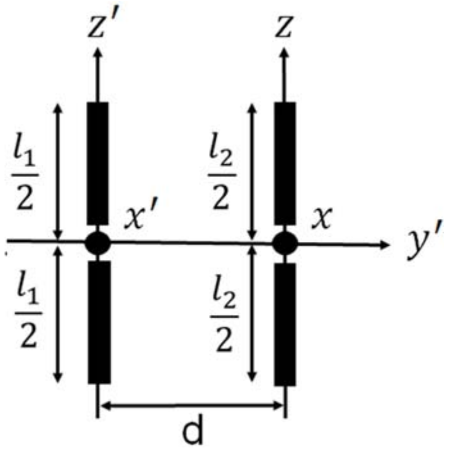


Fig. 3. Two half wavelength dipole antenna array (side by side).

Unlike the general reciprocity characteristic of antenna, Hui proposed for the first time that the effect of mutual coupling can be different based on whether antennas are in the transmitting mode (TRM) or receiving mode (REM) [8]. Therefore, the mutual impedance in TRM or REM has to be analyzed accordingly.

In TRM, the mutual impedance is given by [7]

$$Z_{21(TRM)} = -\frac{1}{I_{1i}I_{2i}}\int_{\frac{-l_2}{2}}^{\frac{l_2}{2}} E_{Z21}\left(z'\right) I_2\left(z'\right) dz' , \qquad (2)$$

where $E_{z21}(z')$ is the electric field element radiated by antenna 1, $I_2(z')$ is the current distribution on antenna 2, and l_2 is the length of antenna 2. I_{1i} and I_{2i} are the input currents of antenna 1 and antenna 2, respectively. In the case of transmitting antenna arrays, open circuit voltage and short circuit current are used to calculate the mutual impedance. Because inducing voltage on dipole antenna 2 can be expressed by

$$v_{2ind} = -\frac{1}{I_{2i}}\int_{\frac{-l_2}{2}}^{\frac{l_2}{2}} E_{Z21}(z') I_2(z') dz' \ . \qquad (3)$$

By combining this with Eq. (2)

$$Z_{21}(TRM) = \frac{V_{2ind}(open\ circuit)}{I_1(short\ circuit)} \ . \qquad (4)$$

In the case of receiving antenna arrays, however, the load connected to antennas should be considered. Fig. 4 shows circuit models to explain the difference between TRM and REM. The mutual impedance of TRM is, thus, from open circuit voltage in Fig. 4(b) divided by short circuit current in Fig. 4(a). The mutual impedance of REM, however, should be from the voltage applied on the load in Fig. 4(d) divided by the current on the load in Fig. 4(c), which can be expressed by

$$Z_{21}(REM) = \frac{V_{2ind}(Load)}{I_1(Load)} \ . \qquad (5)$$

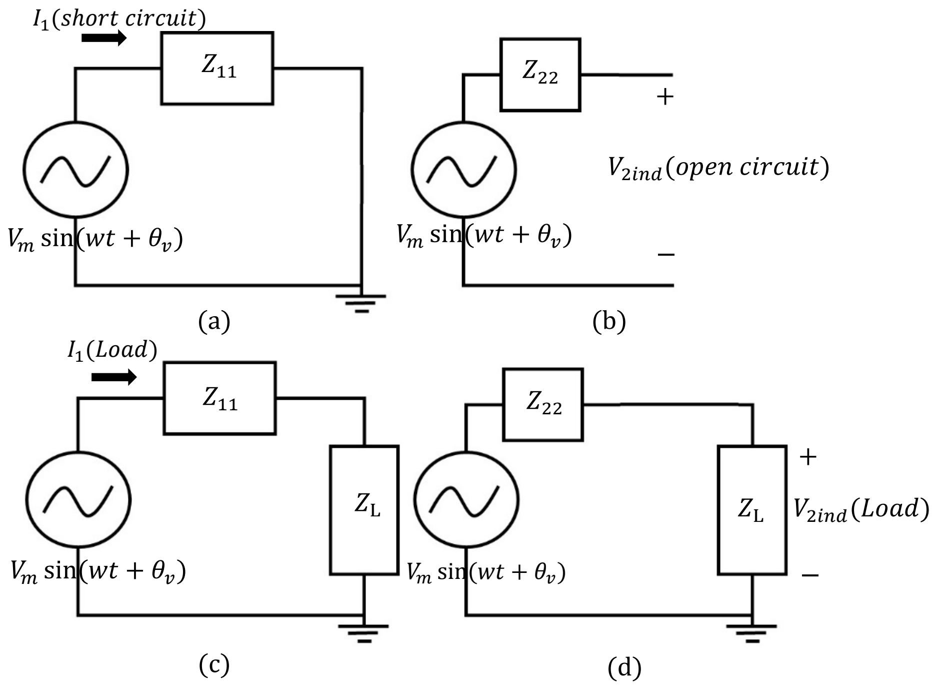


Fig. 4. Circuit models of (a) dipole antenna 1 (short circuit) (b) dipole antenna 2 (open circuit) (c) dipole antenna 1 (Load is connected) (d) dipole antenna 2 (Load is connected).

From Fig. 4(a) and (b), $I_1(short\ circuit)$ and $V_{2ind}(open\ circuit)$ can be written as

$$I_1(short\ circuit) = \frac{V_m\ sin(wt+\theta_v)}{Z_{11}} \tag{6}$$

$$V_2(open\ circuit) = V_m\ sin(wt + \theta_v). \tag{7}$$

From Fig. 4(c) and (d), $I_1(Load)$ and $V_{2ind}(Load)$ can be written as

$$I_1(Load) = \frac{V_m\ sin(wt+\theta_v)}{Z_{11}+Z_L} = \frac{Z_{11}}{Z_{11}+Z_L} * I_1(short\ circuit) \tag{8}$$

$$V_2(Load) = \frac{Z_L}{Z_{11}+Z_L} * V_m si\,n(wt + \theta_v) = \frac{Z_L}{Z_{11}+Z_L} * V_2(open\ circuit) \tag{9}$$

By substituting Eq. (8) and Eq. (9) for Eq. (5), we can derive the mutual impedance of REM.

$$Z_{21}(REM) = \frac{Z_L*(Z_{11}+Z_L)}{Z_{11}*(Z_{22}+Z_L)} * \frac{V_{2ind}(open\ circuit)}{I_1(short\ circuit)} = \frac{Z_L*(Z_{11}+Z_L)}{Z_{11}*(Z_{22}+Z_L)} * Z_{21}(TRM). \tag{10}$$

Because all the dipole antennas in our work have identical specification, the input impedances of dipole antenna 1 and 2, Z_{11} and Z_{22}, are the same. Therefore, the mutual impedance of REM can be simplified further:

$$Z_{21}(REM) = \frac{Z_L}{Z_{11}} * Z_{21}(TRM). \tag{11}$$

In conclusion, the ratio of load and input impedance causes the difference between the mutual impedances of TRM and REM.

The difference between transmitting and receiving mutual impedances in terms of magnitude and phase is exhibited in Fig. 5. We also compare the mutual impedance of simulation results by using HFSS, electromagnetic fields simulation software. Because HFSS is designed for TRM mode, but not for REM, HFSS results have similar plots with TRM analysis. Fig. 5 shows that the effect of mutual coupling is increased if the spacing of antennas is small in the range of d/λ < 1. On the other hand, if the interval between antennas is very large with d/λ > 1, mutual coupling effect decreases. Since RF energy harvesting is to capture external source energy by definition, the receiving (REM) mutual impedance should be used for analyzing our

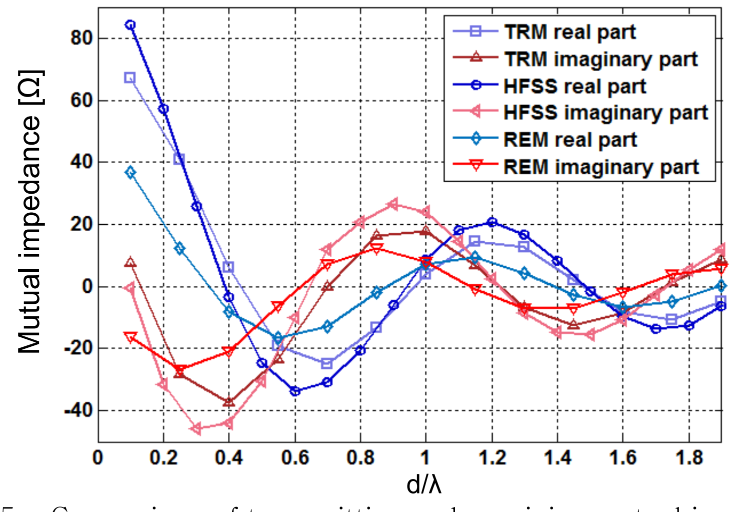


Fig. 5. Comparison of transmitting and receiving mutual impedances.

experiments.

2.2 In energy harvesting

In previous section, the mutual coupling between dipole antennas was analyzed by modeling mutual impedance [7]–[8]. The polarity of mutual impedance changes depending on the spacing of antennas, which implies that the mutual coupling can affect the received power of antennas in a positive or negative way.

In multi–input multi–output (MIMO) systems, Wallace showed that two closely arranged antennas can gather more power than the non–coupling case from simulation results [9]. While mutual coupling has advantages in terms of collecting more power, previous works about rectenna arrays have considered only that mutual coupling has negative effects on the received power. It is regarded as the error factor [10] and antenna spacing is selected large enough to avoid the mutual coupling effect [11]. The purpose of this section is to investigate the advantage of the mutual coupling effect between half wavelength dipole antenna arrays for RF energy harvesting by conducting two–dipole array experiments in the low frequency anechoic chamber and then we extend our analysis to arrays of more than two antennas.

2.2.1 Equivalent circuits of dipole antenna

Fig. 6 shows the equivalent circuits of dipole antenna for the non–coupled and the coupled case, respectively.

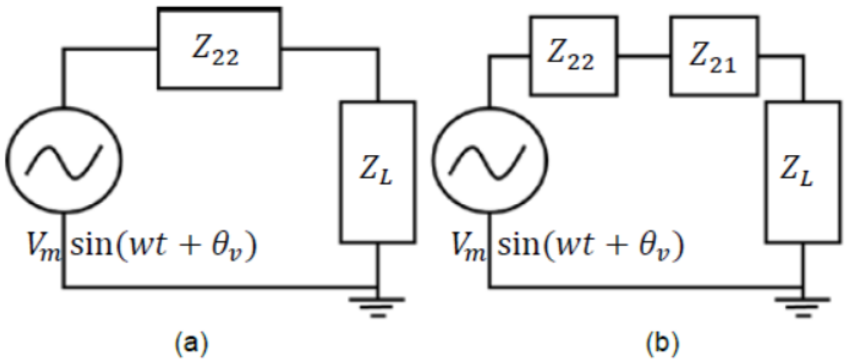


Fig. 6. Equivalent circuits of dipole antenna 2 with input impedance Z_{22}, mutual impedance Z_{21}, load impedance Z_L and applied voltage V_{m}: (a) uncoupled case (b) coupled

In the uncoupled case, the received power is given by

$$P_{uncoupled} = \frac{1}{2} {V_m}^2 Re\left\{\left(\frac{Z_L}{|Z_{22}+Z_L|^2}\right)\right\}, \tag{12}$$

where Z_{22} is the input impedance of antenna 2, Z_L is the load impedance, and V_m is the applied voltage. However, in the coupled case, the mutual impedance has to be considered in calculating the received power, which is given by

$$P_{coupled} = \frac{1}{2} {V_m}^2 Re\left\{\left(\frac{Z_L}{|Z_{22}+Z_{21}+Z_L|^2}\right)\right\}, \tag{13}$$

where Z_{21} is the mutual impedance.

In the uncoupled case, maximum power transfer is achieved by using the conjugate matching circuit.

$$\begin{aligned} P_{uncoupled} &= \frac{1}{2} {V_m}^2 Re\left\{\left(\frac{Z_L}{|Z_{22}+{Z_L}^*|^2}\right)\right\} \\ &= \frac{1}{2} {V_m}^2 Re\left\{\left(\frac{R_{22}-jX_{22}}{|R_{22}+jX_{22}+R_{22}-jX_{22}|^2}\right)\right\} \\ &= \frac{1}{2} {V_m}^2 Re\left\{\left(\frac{R_{22}-jX_{22}}{|2R_{22}|^2}\right)\right\} \\ &= \frac{1}{8} \frac{{V_m}^2}{R_{22}}. \end{aligned} \tag{14}$$

In the coupled case, Eq. (15), however, the mutual coupling effect changes the input impedance of dipole antenna and results in variation of the received power. In Eq. (13), whenever the polarity of mutual impedance is negative with respect to other impedances, the denominator of the received power decreases and thus the received power increases.

$$P_{coupled} = \frac{1}{2}{V_m}^2 Re\left\{\left(\frac{Z_L}{|Z_{22}+Z_{21}+{Z_L}^*|^2}\right)\right\}$$

$$= \frac{1}{2}{V_m}^2 Re\left\{\left(\frac{(R_{22}+R_{21})-j(X_{22}+X_{21})}{|(R_{22}+R_{21})+j(X_{22}+X_{21})+(R_{22}+R_{21})-j(X_{22}+X_{21})|^2}\right)\right\}$$

$$= \frac{1}{2}{V_m}^2 Re\left\{\left(\frac{(R_{22}+R_{21})-j(X_{22}+X_{21})}{|(R_{22}+R_{21})+j(X_{22}+X_{21})+(R_{22}+R_{21})-j(X_{22}+X_{21})|^2}\right)\right\}$$

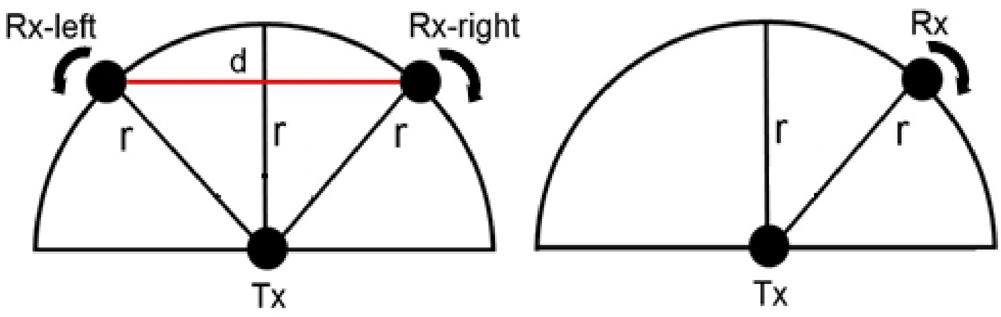
$$= \frac{1}{2}{V_m}^2 Re\left\{\left(\frac{(R_{22}+R_{21})-j(X_{22}+X_{21})}{|2(R_{22}+R_{21})|^2}\right)\right\}$$

$$= \frac{1}{8}{V_m}^2\left(\frac{1}{R_{22}+R_{21}}\right). \qquad (15)$$

Therefore, the spacing of antenna is large enough to ignore mutual coupling, the conventional form of matching circuit can maximize the received power. However, when antennas are closely spaced, the received power of each antenna is affected by mutual coupling, and thus, mutual coupling has to be considered in designing the matching circuit.

2.2.2 Experiment setup

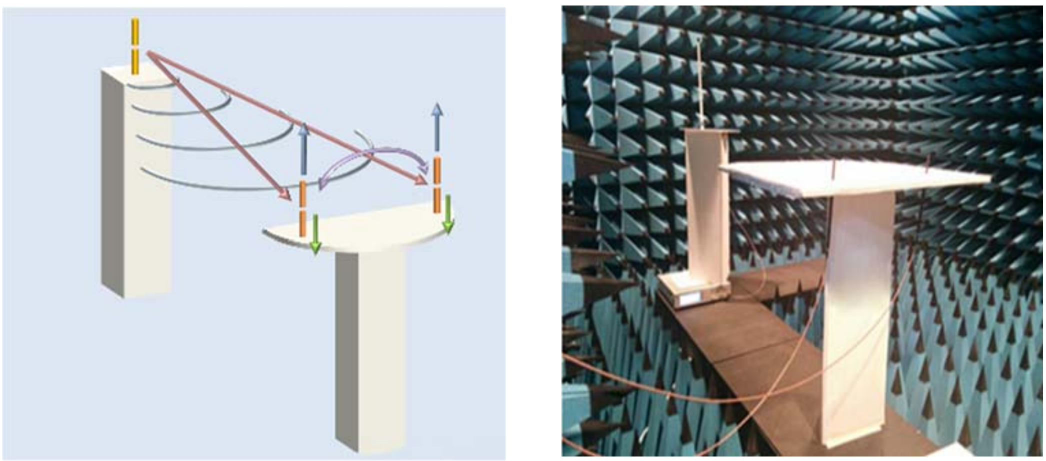
To investigate the mutual coupling effect, we perform experiments for uncoupled and coupled cases, respectively half wavelength dipole antennas at 1.2 GHz are used in our experiment setup of Fig. 7. With spherical waves incident to receiving antennas (Rx’s), we measure the received power by changing the distance between Rx's. We fix the distance from the transmitting antenna (Tx) to each of Rx’s at 2 m and rotate the Rx’s on the half circle as shown in Fig. 7(a), so that our experiment can avoid the mutual coupling effect between transmitting antenna (Tx) and Rx’s. The distance between two Rx’s are increased from 0.1 λ to 1.90 λ by 0.15 λ, the smallest interval that can be implemented in our experiment, considering the thickness of antenna. For the uncoupled case in Fig. 7(b), the same distance of 2 m between Tx and Rx is maintained and a single Rx on the quarter circle is measured at the same points as for the coupled case.



(a) (b)

Fig. 7. Comparison of (a) coupled and (b) uncoupled case. d is the distance between receiving antennas, and r is the distance between Tx and Rx.

Fig. 8 shows our experiment setup to identify mutual coupling in the receiving antenna array. Since Styrofoam and air have almost the same relative permittivities of 1.03 and 1.0005, respectively [12], antennas on Styrofoam can be assumed to be arranged in the air. The Tx antenna is connected to a signal generator while the Rx antennas are plugged into spectrum analyzers. To minimize error, experiments are conducted three times in the low frequency anechoic chamber and the average of results is used for our analysis.



(a) (b)

Fig. 8. Experiment setup: (a) Scheme of two dipole array experiments (b) Picture of the low frequency anechoic chamber.

2.2.3 Experiment results & discussion

In Fig. 9 we compare theoretical and experimental results in the coupled and uncoupled cases, respectively. The received power in uncoupled case is given as a constant regardless of d/λ and compared with that in coupled case. Because the dipole antenna used in the experiment is not exactly omnidirectional, we average the measured values at the different points as the antenna rotates on the quarter circle. Also theoretical results of uncoupled case are calculated by Friis equation which is given by

$$\frac{P_{uncoupled}}{P_t} = (\frac{\lambda}{4\pi r})^2 G_{0t} G_{or}, \tag{16}$$

where P_t is the transmitted power, G_{0t} is the gain of transmitting antenna, G_{or} is the gain of receiving antenna, r is the distance between transmitting antenna (Tx) and receiving antenna (Rx). The transmitted power is set to be 1mW, the gains of transmitting antenna and receiving antenna are 7dBi and 2dBi (from the specification of antenna used in our experiments.), respectively, λ is 0.25 m, and r is 2m. From Eq. (R11), $P_{uncoupled}$ is 2.110 uW.

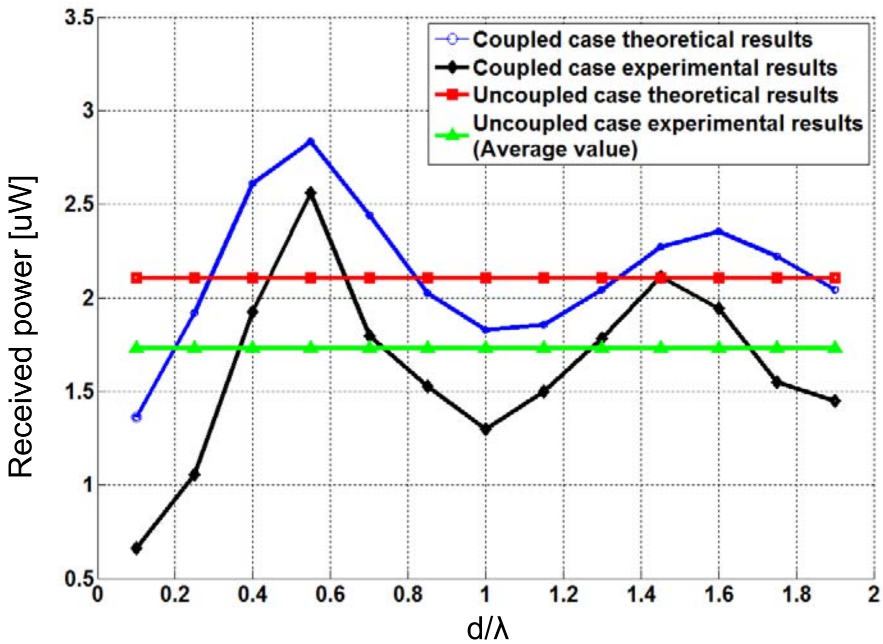


Fig. 9. Per−antenna received power of dipole antennas.

Our experimental results reveal that the received power of the coupled case can be more than that of the uncoupled case in some points. In particular, when the spacing of antenna is near 0.55 λ, the experimental value of 2.55 μW (per antenna) in the coupled case is 1.5 times as large as the uncoupled received power (1.730 uW). Our study also shows that the mutual coupling effect can be either positive or negative, depending on antenna spacing. If the spacing of antenna is 1.0 λ, the received power of 1.30 μW is lower than that of the uncoupled case. Proximity within 0.3 λ induces strong mutual coupling impedance in terms of a large absolute value but this rather decreases the received power, lower than that of the uncoupled case, because the complex value is not conjugate matched to the input and load impedance values. It is summarized in TABLE 1.

TABLE 1: Mutual impedance and the received power

Distance [λ]	Mutual impedance $Z_{21}(REM)$ [Ω]	Absolute value of mutual coupling $\lvert Z_{21}(REM)\rvert$	Denominator of the received power equation $\lvert Z_{22}+Z_{21}(d)+Z_L\rvert^2$	The received power [uW]
0.1	36.6899-16.1976i	40.110	$2.6193*10^4$	1.360
0.55	-16.7243-6.3027i	17.870	$1.2605*10^4$	2.840
1.00	7.33620+7.8813i	10.770	$1.9526*10^4$	1.830
1.50	-4.6300-5.7323i	7.3686	$1.5363*10^4$	2.325

From TABLE 1, when the spacing of antenna gets large, the absolute value of mutual coupling is decreased. However, the matching of mutual impedance to other impedances, rather than the absolute value, has to be considered in the received power, as illustrated in the denominator values of the received power equation. In Eq. (13), the received power is reduced at 0.1 λ regardless of the increased absolute value of $\mathbf{Z_{21}}$. We see the opposite results at 0.55 λ. In other words, when the distance is less than 0.3 λ, the effect of mutual impedance to the received power is negative as it increases the denominator of the received power equation ($\lvert Z_{22}+Z_{21}(d)+Z_L\rvert^2$) even if the absolute value of mutual coupling is enhanced.

In addition, Fig. 9 shows that the mutual coupling effect diminishes as the interval of antennas increases. Experimental results in the coupled and uncoupled cases converge as the spacing of antennas increases.

From our experimental results, when the interval of antenna is large enough to avoid the mutual coupling, the total received power is 3.46 uW. On the contrary, if the spacing of antenna is properly set to utilize the mutual coupling, the total received power increases to 5.10 uW as shown in Fig. 10, suggesting that exploiting the mutual coupling can increase the total received power.

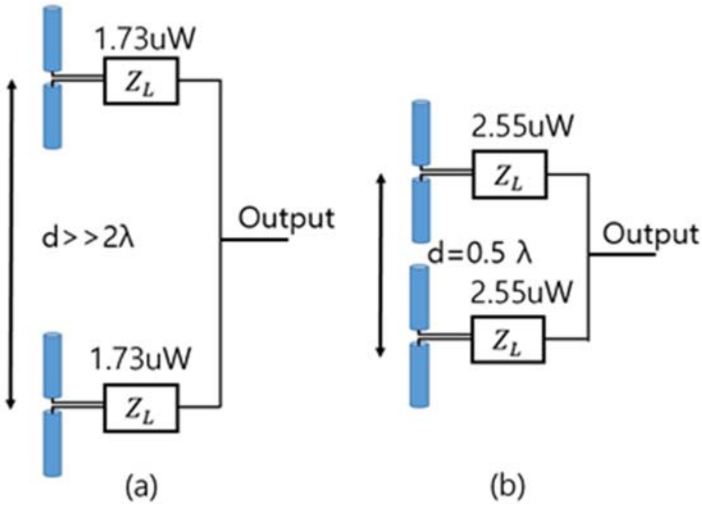


Fig. 10. The received power of dipole antenna: (a) the uncoupled case (b) the coupled case with mutual coupling increasing the received power.

2.2.4 Generalization of mutual coupling for more than two dipole antennas

When more than two antennas are arranged, each antenna is affected by adjacent antennas, depending on the spacing of antennas and showing a periodic pattern. Based on theoretical results, whenever the interval of antennas is around $(1/2)\lambda + k\lambda$ (k=0, 1, 2, ... m), antennas have the positive influence to each other, reducing the total input impedance. The antenna spacing close to $k\lambda$ increases impedances, on the other hand.

Now we generalize mutual coupling from two to n (> 2) dipole antenna array. In our modeling, each dipole is apart from the nearest neighbor with the equal distance d, as illustrated in Fig. 11. For each antenna we calculate mutual impedance and the received power, by generalizing mathematical analysis in Eq. (10) and Eq. (13). We use MATLAB for complex calculations.

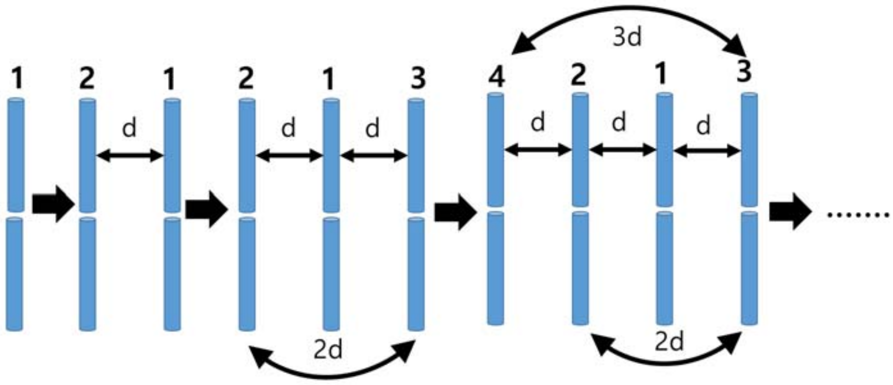


Fig. 11. The received power of dipole antenna

For example, when three dipole antennas are arranged with d = 0.5 λ, we calculate the received power of each antenna, analytically given by

$$P_1(d) = \frac{1}{2}{V_m}^2 Re\left\{\left(\frac{Z_L}{|Z_{11}+Z_{12}(d)+Z_{13}(d)+Z_L|^2}\right)\right\}, \tag{17}$$

$$P_2(d) = \frac{1}{2}{V_m}^2 Re\left\{\left(\frac{Z_L}{|Z_{22}+Z_{21}(d)+Z_{23}(2d)+Z_L|^2}\right)\right\}, \tag{18}$$

$$P_3(d) = \frac{1}{2}{V_m}^2 Re\left\{\left(\frac{Z_L}{|Z_{33}+Z_{31}(d)+Z_{32}(2d)+Z_L|^2}\right)\right\}. \tag{19}$$

Results of the received power of each antenna (P_1, P_2, and P_3) are 4.0123 uW, 2.4245 uW, and 2.4245 uW, respectively. $P_2(d)$ and $P_3(d)$ are equal because of symmetry. The total received power of $P_1(d) + P_2(d) + P_3(d) =$ 8.8612 uW is more than the three times of uncoupled received power, 3*$P_{uncoupled}$=6.3278 uW. Not only the center antenna (antenna 1) but antennas on each side (antenna 2 and antenna 3) can capture more power than the uncoupled antenna. For five dipole antennas, the received power values of each antenna (P_1, P_2, P_3, P_4, and P_5) are 2.8175 uW, 3.7609 uW, 3.7609 uW, 2.4905 uW, and 2.4905 uW, respectively. We can show again that the total received power of 15.3186 uW is more than the five times of the uncoupled case ($5*P_{uncoupled}$=10.5463 uW).

In this way, we calculated the received power up to 20 antennas, as summarized in TABLE 2 and Fig. 12. As the number of arranged antennas increases, the average received power per antenna converges to 3.20 uW with some fluctuation, larger than the uncoupled case of 2.1093 uW by 1.510 times. We conclude that the harvesting power can be enhanced up to 51% by exploiting the mutual coupling effect.

TABLE 2: The received power ratio of the coupled case and uncoupled case

Number of arranged antennas	Total received power [uW]	Average received power of the unit antenna [uW]	N times of the received power of uncoupled [uW]	Received power of uncoupled case [uW]	Ratio of the coupled case and uncoupled case
1	2.1093	2.1093	2.1093	2.1093	1.0000
2	5.6925	2.8462	4.2185	2.1093	1.3494
3	8.8612	2.9537	6.3278	2.1093	1.4004
4	12.8281	3.2070	8.4371	2.1093	1.5204
5	15.3186	3.0637	10.5463	2.1093	1.4525
6	19.2285	3.2047	12.6556	2.1093	1.5194
7	21.7454	3.1065	14.7649	2.1093	1.4728
8	25.6346	3.2043	16.8742	2.1093	1.5192
9	28.1655	3.1295	18.9834	2.1093	1.4837
10	32.0440	3.2044	21.0927	2.1093	1.5192
11	34.5835	3.1440	23.2020	2.1093	1.4905
12	38.4554	3.2046	25.3112	2.1093	1.5193
13	41.0007	3.1539	27.4205	2.1093	1.4953
14	44.8682	3.2049	29.5298	2.1093	1.5194
15	47.4177	3.1612	31.6390	2.1093	1.4987
16	51.2818	3.2051	33.7483	2.1093	1.5195
17	53.8345	3.1667	35.8576	2.1093	1.5013
18	57.6962	3.2053	37.9668	2.1093	1.5196
19	60.2514	3.1711	40.0761	2.1093	1.5034
20	64.1110	3.2056	42.1854	2.1093	1.5197

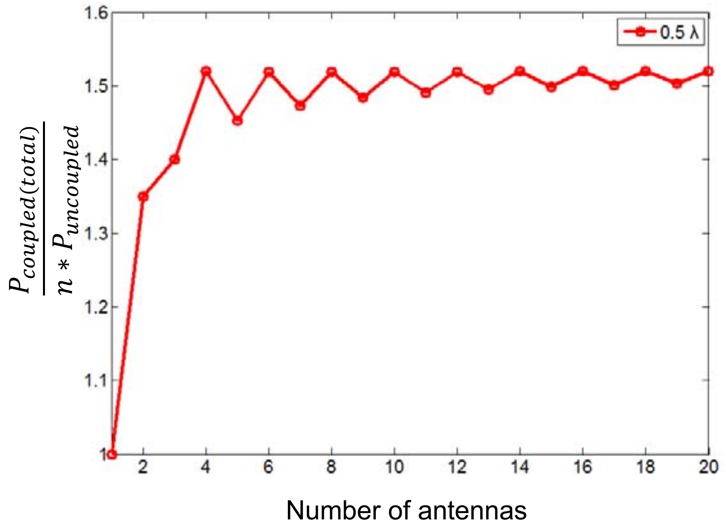


Fig. 12. The power gain of the coupled case.

Previously we mentioned that the mutual coupling effect can be either positive or negative. In Fig.13, with the interval of antennas equal to 0.1 λ, 1.0 λ, or 2.0 λ, the power gain is lower than 1.0, meaning that mutual coupling negatively affects the received power. On the other hand, if the spacing of antenna is 0.5 λ or 1.5 λ, the power gain is 1.5197 or 1.1460, respectively with the positive mutual coupling effect. The converged value of the power gain, shown in Fig. 13 as the number of antennas increases, is plotted for each distance in Fig. 14. We observe the power gain of 0.9651 when the interval of antenna is 20.0 λ, implying that mutual coupling almost disappears to the uncoupled case as the distance of antenna increases. It is remarked that the theoretical power gain of 1.34 at 0.55 λ calculated from Fig. 9 is comparable to the result of 1.35 at 0.5 λ in Fig. 13. Fig. 15, plots the power gain in 3D as a function of the spacing and the number of antennas.

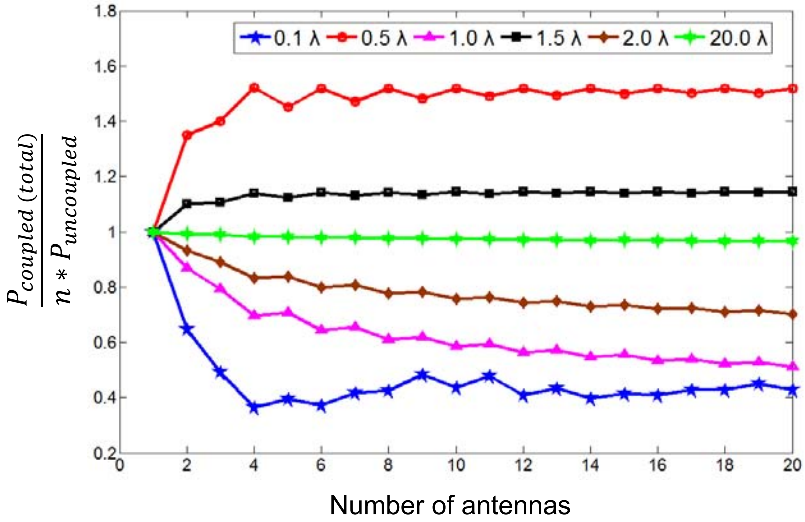


Fig. 13. Analytical results of power gains of the coupled case depending on the number and spacing of antenna.

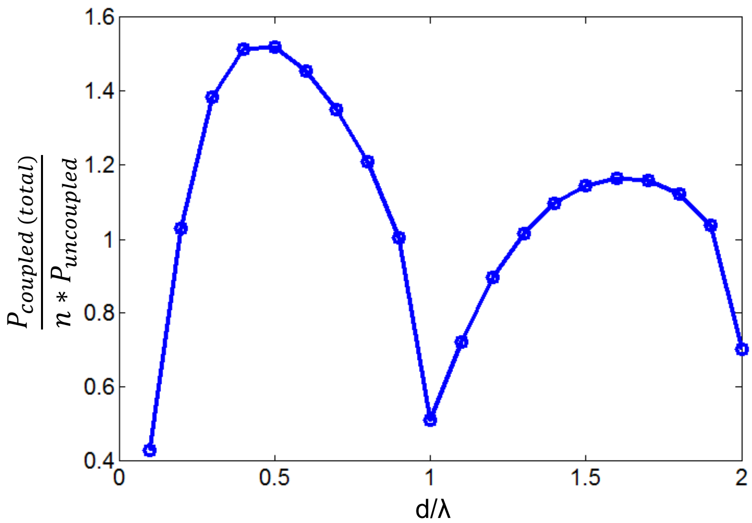


Fig. 14. Converged value of the ratio of received power

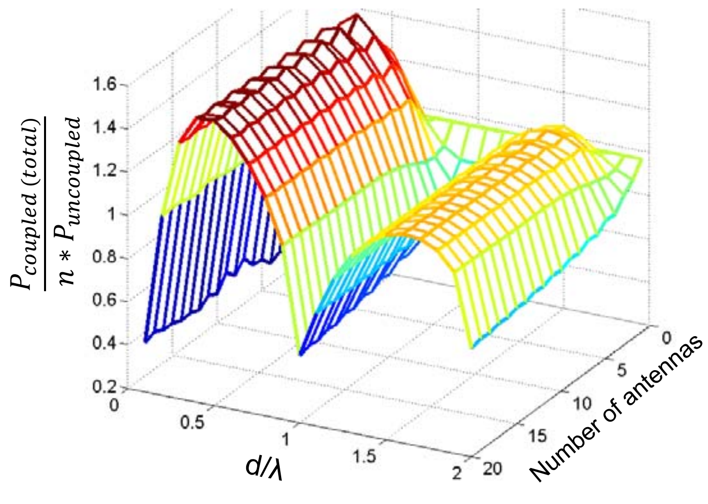


Fig. 15. The ratio of the coupled case and uncoupled case: depending on the number and spacing of antenna.

2.3 In channel capacity

In the presence of mutual coupling effects, because of the channel gain matrix change that describes the channel state, the channel capacity is also affected by mutual coupling. Channel capacity that includes the mutual coupling effect was discussed in [13]−[14]. In [13], the spatial correlation coefficient can be reduced by mutual coupling, which leads to increase of the channel capacity in multiple−input multiple−out (MIMO) systems. The relationship between channel capacity in MIMO systems and mutual coupling in different channel environments such as the Rician channel and Rayleigh channel was discussed in [14]. Also, because the spatial correlation coefficient that includes mutual coupling effect depends on the antenna load impedance the load have to be considered in the spatial correlation [15]. The transmitting mode mutual impedance to model the coupling between antennas, however, was used in analyzing the channel capacity in [13]−[14]. Because SWIPT is in the receive mode, the receiving mode mutual impedance has to be used in calculating the channel capacity.

In this section, mutual coupling and the channel capacity in single−input multiple−output (SIMO) systems are discussed.

2.3.1 SIMO system model

As shown in Fig. 16, we first study a wireless communication link with one transmit antenna (n_t) and n_r receive antennas. At the transmit antenna, the transmitted signals are expressed as $\mathrm{s} = [\mathrm{s1}\,\mathrm{s2} \ldots \mathrm{sn}]^T$, where $\mathrm{s1}$, $\mathrm{s2}$, ..., and sn are the transmitted signals to the receive antenna 1, 2, ..., n. The channel matrix H consists of channel parameters as follows:

$$\mathrm{H} = \begin{pmatrix} h_{n_t1} & 0 & \cdots & 0 \\ 0 & h_{n_t2} & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & & \cdots & h_{n_tn_r} \end{pmatrix}, \tag{20}$$

where $h_{i,i}$ denotes the channel parameter between the ith transmit antenna and the ith receiver element, it is given by

$$h_i = a\exp\left(-\frac{j2\pi f_c d_i}{c}\right) = a\exp\left(-\frac{j2\pi d_i}{\lambda_c}\right) \quad [16], \qquad (21)$$

where a is the attenuation of the path, f_c is the carrier frequency, and d_i is the distance between transmitting antenna and i−th receiver. Transmitted signals undergo path loss by propagating wireless link. Thus the received signal $r = [r1\ r2 \ldots rn]^T$ is given by $r = Hs + n$, where n is temporally additive white Gaussian noise (AWGN) with unit variance.

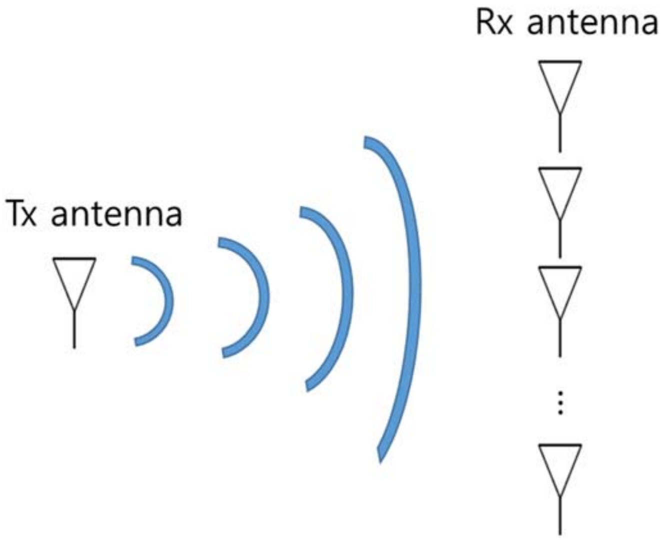


Fig. 16. SIMO systems

2.3.2 Mutual coupling matrix

Assume that the array with n_R receivers is placed in a free space. A matrix relationship between the coupled voltage and the uncoupled voltage on antenna can be expressed as [17]

$$V = MV_{oc}, \qquad (21)$$

where V is the coupled voltage, M is the mutual coupling matrix, and V_{oc} is the open circuit voltage that represents the voltage under stand−alone conditions. In [17], however, the open circuit voltage is used for calculating the mutual coupling matrix. With practical issues, the voltage at the load is discussed in[18].

Consider an receive antenna array with N elements, where each of these is connected with the load impedance Z_L. When electromagnetic waves are incident to the antenna array, the voltage at the load V_k can be written as

$$V_k = -Z_L I_k = U_k + W_k \quad [18], \tag{22}$$

where U_L is the voltage under the stand−alone conditions, I_k is the current on the k−th antenna, and W_k is the voltage due to the mutual coupling effect from adjacent receive antennas. W_L can be expressed as

$$W_k = Z_{k,1}I_1 + Z_{k,2}I_2 + Z_{k,k-1}I_{k-1} + \ \ldots + Z_{k,N}I_N \quad [18], \tag{23}$$

where $Z_{k,i}$ is the receiving mode mutual impedance between the k−th and i−th antenna, and I_i is the current that flows on antenna i. From Eq. (22) and Eq. (23), we can derive the relationship [18] between U_k and V_k as

$$\begin{bmatrix} 1 & \cdots & \frac{Z_{1,N}}{Z_L} \\ \vdots & \ddots & \vdots \\ \frac{Z_{N-1,1}}{Z_L} & \cdots & 1 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_N \end{bmatrix} \quad [18]. \tag{24}$$

From Eq. (21), the mutual coupling matrix can be written as

$$\mathrm{M} = \begin{bmatrix} 1 & \cdots & \frac{Z_{1,N}}{Z_L} \\ \vdots & \ddots & \vdots \\ \frac{Z_{N-1,1}}{Z_L} & \cdots & 1 \end{bmatrix}^{-1}. \tag{25}$$

2.3.3 Channel capacity with mutual coupling effect

To calculate the channel capacity under coupling conditions, the channel matrix has to be modified with the mutual coupling effect. A new channel matrix with the mutual coupling into consideration can be derived by multiplying the coupling matrix M for a receiver [13]. Therefore, the SIMO systems is given by

$$\mathrm{r} = \mathrm{CHs} + \mathrm{n} = H_c s + n, \tag{26}$$

where H_c is the new channel matrix,.

Based on information theory, the channel capacity is defined as maximum of the mutual information [19]:

$$\begin{aligned} \mathrm{C} &\triangleq \mathrm{Max}\, \mathrm{I(X;Y)} \\ &= Max\,\{H(Y) - H(Y|X)\}, \end{aligned} \tag{27}$$

where C is the channel capacity, I(X;Y) is the mutual information between input X and output Y, and H is the entropy. In SIMO systems, because the input is the transmitted signal s and the output is the received signal r, the mutual information can be written as

$$\begin{aligned} \mathrm{I(X;Y)} &= \mathrm{H(Y)} - \mathrm{H(Y|X)} \\ &= \mathrm{H(r)} - \mathrm{H}(H_c s + n|s) \\ &= \mathrm{H(r)} - \mathrm{H(n)}. \end{aligned} \tag{28}$$

By adapting the definition of entropy to Eq. (28) and Eq. (27), the channel capacity can be derived as follows

$$C = \log_2 \left| I + \frac{1}{\sigma^2} H_c R_{ss} {H_c}^H \right| \text{ (bits/sec/Hz)}, \tag{29}$$

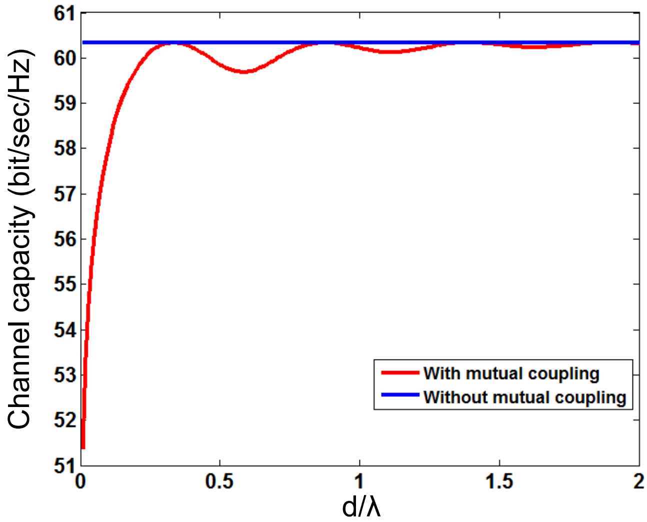
where I denotes the identity matrix, σ^2 is the variance of AWGN, R_{ss} is the covariance matrix of signals, $|\cdot|$ means the determinant, and ${H_c}^H$ the Hermitian matrix of H_c. To express Eq. (29) as in terms of signal to noise ratio (SNR), the channel matrix has to be changed to H′ with satisfying $||H'||_F{}^2 = n_r$ and the variance of signal is $\sigma^2 = \frac{1}{n_t}$. Finally, the channel capacity in SIMO systems is given as

$$C = \log_2 \left| I + \rho H' ({H'}^H) \right| \text{ (bits/sec/Hz)}, \tag{30}$$

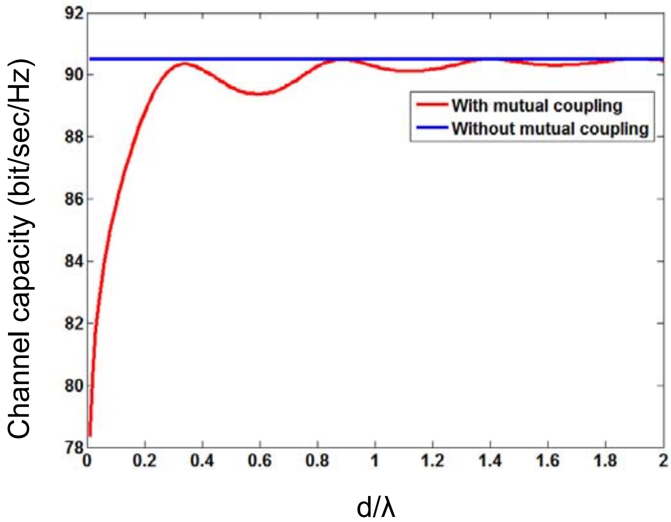
where ρ represents the SNR.

The channel capacity with different spacing of antenna is plotted in Fig. 17. The specification of antenna is the same for the case of energy harvesting previously discussed. When dipole antennas are arranged, the channel capacity fluctuates as the interval of antenna is changed. In addition because the impact of mutual coupling decreases as the spacing of antennas is larger, the channel capacities of the coupled and uncoupled case are converged.

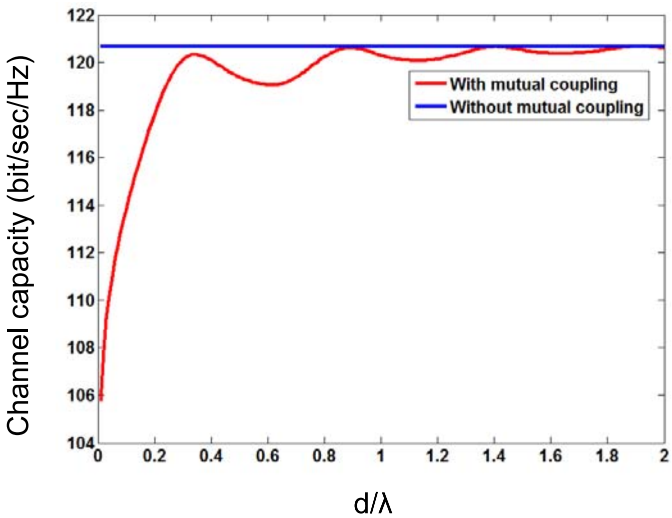
At some points, despite strong coupling, the channel capacity becomes large as much as the uncoupled case. Because the re−radiated electromagnetic waves from the receive antennas cancel out each other’s electromagnetic waves, the coupling elements disappear. Mathematically, the mutual coupling matrix approaches the identity matrix and receivers operate in stand−alone conditions.



(a)



(b)



(c)

Fig. 17 The channel capacity with spacing of antennas : (a) Rx=2 (b) Rx=3 (c) Rx=4

III. OPTIMIZATION

Since the mutual coupling causes the distortion of the received power and channel capacity in SIMO systems, to select the proper distance between antennas is important in designing SWIPT. Spacing of antenna is different depending on purpose. For example, if high throughput is needed, the interval of antenna have to be set to maximize the channel capacity and when sensors require a large amount of power the distance of antenna adjust for maximizing the received power. Finding to optimal distance depending on the purpose can be modeled as optimization problems.

3.1 Optimization modeling

Consider situation that unit antenna cannot harvest enough energy to operate ultra−low power sensors. To guarantee operation of ultra−low power sensors, the antenna arrays are required. Since the mutual coupling caused by arranging antenna affects the performance on the received power and channel capacity depending to the distance between antennas, it has to be considered. In this situation, the spacing of antenna have to set to increase the harvested energy to supply enough power to the ultra−low power sensors. Also, the channel capacity have to be maximized for reliable communications. Therefore, these problems can be modeled as follows:

$$\begin{aligned} &\text{Maximize} \quad C_{SIMO}(d) \\ &\text{Subject to} \quad P_{Harvesting}(d) \geq P_{Requried} \end{aligned} \tag{31}$$

where $C_{SIMO}(d)$ is function of the channel capacity in SIMO systems, $P_{Harvesting}(d)$ is the harvested power, and $P_{Requried}$ is the required power to operate ultra−low power sensors. The verification that whether the functions which are dealt with have the convexity or not should be performed to solve the optimization problems and it can be conducted by using

Hessian operation. If the function f is twice differentiable or its Hessian exists at each point in domain f and Hessian is positive semidefinite, the function f is convex [20].

$$\nabla^2 f(x) \succcurlyeq 0. \tag{32}$$

Similarly, f is concave if Hessian is negative semidefinite for all domain ($\nabla^2 f(x) \preccurlyeq 0$).

When two dipole antennas are arranged, Hessian of channel capacity and the received power is plotted in Fig. 18. Because two functions have both positive and negative value for domain, they are non-convex function.

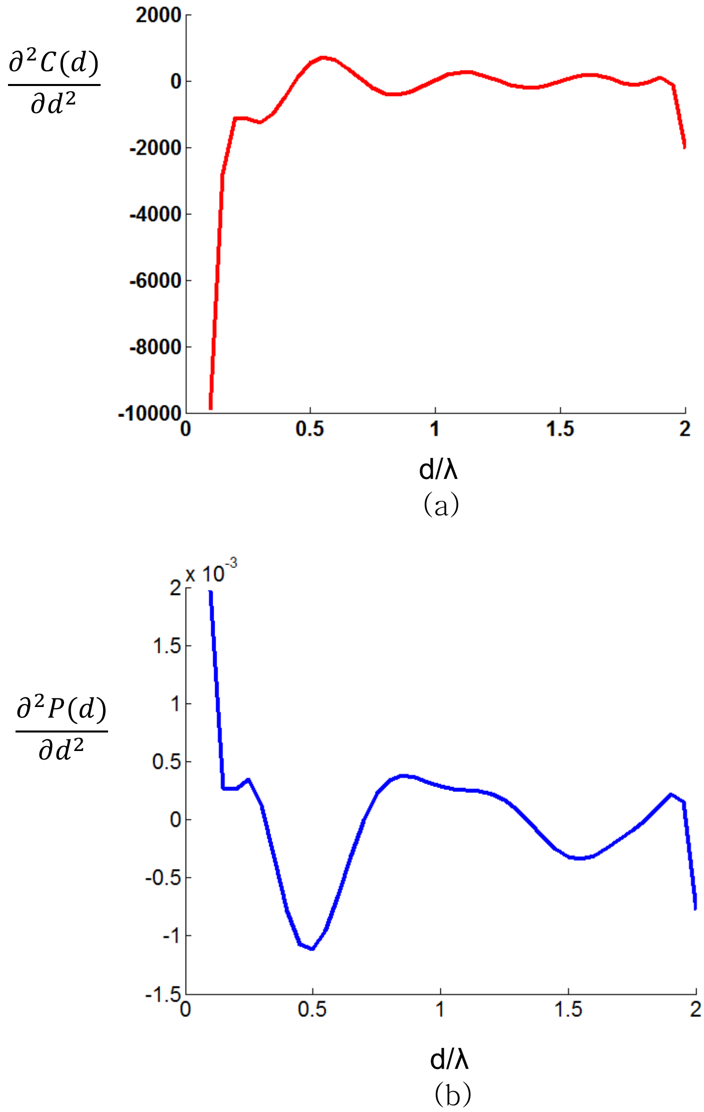


Fig. 18. Results of Hessian operation: (a) For channel capacity (b) For Received power.

After converting Eq. (32) into standard form, to find the proper distance that satisfies with the constraint condition and objective, the Lagrange multiplier method is used.

$$\begin{aligned} &\text{Minimize} && -C_{SIMO}(d) \\ &\text{Subject to} && P_{Requried} - P_{Harvesting}(d) \leq 0 \ . \end{aligned} \tag{34}$$

3.2 Lagrange multiplier method

Lagrange multiplier method connects the objective function and constraint conditions by introducing variables called 'Lagrange multiplier". The function that results from Lagrange multiplier method is named "Lagrange dual function". Because the Lagrange dual function is unconstrained function, the optimal solution can be derived easily. In following sections, method of making the Lagrange dual function and finding the solution are discussed.

3.2.1 KKT conditions

The following four conditions are called KKT conditions [20].

1. Primal constraints : $f_i(x) \leq 0,\ i = 1, \dots, m,\ \ h_i(x) = 0, i = 1, \dots, p$
2. Dual constraints: $\lambda \geq 0,\ v \geq 0$
3. Complementary slackness: $v_i f_i(x) = 0, i = 1, \dots, m$
4. Gradient of Lagrangian with respect to x vanishes:

$$\nabla f_0(x) + \sum_{i=1}^{m} \mathrm{v}_i \nabla f_i(x) + \sum_{i=1}^{p} \lambda_i \nabla h_i(x) = 0$$

The first and second condition of KKT are useful to link between the objective function and constraint conditions in terms of assigning the sign. From these conditions, the Lagrange dual function for Eq. (34) is given by

$$\mathrm{L}(\mathrm{d},\mathrm{v}) = -C_{SIMO}(d) - \mathrm{v} * (\ P_{Requried} - P_{Harvesting}(d)\ )\ , \tag{35}$$

where L is the Lagrange dual function, v is the Lagrange multiplier. Then the optimal solution can be derived from the third and fourth of KKT. In the process of solving the equation, however, because the channel capacity and received power include the complex integral equation, it is difficult to solve the simultaneous equations. Therefore, the method of undetermined coefficients that convert the complex functions to the polynomial equations is used as alternative.

3.2.2 Method of undetermined coefficients

Assume that function of the channel capacity depending to the spacing of antenna is given by

$$\begin{bmatrix} 1 & d_0 & {d_0}^2 & \dots & {d_0}^n \\ 1 & d_1 & {d_1}^2 & \dots & {d_1}^n \\ & & \vdots & & \\ 1 & d_n & {d_n}^2 & \dots & {d_n}^n \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} C_{SIMO}(d_0) \\ C_{SIMO}(d_1) \\ \vdots \\ C_{SIMO}(d_n) \end{bmatrix}\ , \tag{36}$$

where $a_0, a_1, a_2, \dots, a_n$ are the undetermined coefficients. To find the value of undetermined coefficient, the pseudo inverse is conducted because the left side matrix is not square matrix.

$$\begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_n \end{bmatrix} = \begin{bmatrix} C_{SIMO}(d_0) \\ C_{SIMO}(d_1) \\ \vdots \\ C_{SIMO}(d_n) \end{bmatrix} \begin{bmatrix} 1 & d_0 & {d_0}^2 & \dots & {d_0}^n \\ 1 & d_1 & {d_1}^2 & \dots & {d_1}^n \\ & & \vdots & & \\ 1 & d_n & {d_n}^2 & \dots & {d_n}^n \end{bmatrix}^{-1} . \tag{37}$$

Therefore, the function of channel capacity can be expressed as follows:

$$C_{SIMO}(d) = a_0 + a_1 d + a_2 d^2 + a_3 d^3 + \dots + a_n d^n. \tag{38}$$

Likewise, the received power also can be derived:

$$P_{Harvesting}(d) = b_0 + b_1 d + b_2 d^2 + b_3 d^3 + \dots + b_n d^n, \tag{39}$$

where $b_0, b_1, b_2, \dots, b_n$ are the undetermined coefficients. Since Eq. (38) and Eq. (39) are function of the polynomial, simultaneous equations from KKT conditions can be solved easily.

For example, when two dipole antennas are arranged, sensor require the power for operating amount of 4.5uW, and high throughput is needed, we can model this problem same as Eq. (34). By using Lagrange multiplier methods, we can derive solution as d=0.3490 λ, v=0.00, C(0.3490 λ)=60.3563 [bit/sec/Hz], and P(0.3490 λ)= 4.77 [uW].

IV. CONCLUSION

The mutual coupling effect in SWIPT has been investigated in terms of the performance on the received power and channel capacity. In respects of energy harvesting, to prove the advantage of the mutual coupling effect, dipole array experiments have been conducted in the low frequency anechoic chamber. The experimental results on two dipole array demonstrate that when the spacing of antenna is near half wavelength, the received power of the coupled case can be maximized. The mutual coupling effect diminishes as the interval of dipole antennas increases. Furthermore, we have attempted to generalize our analysis for more than two half wavelength dipole antennas, and shown that the power gain of more than 50% can be achieved by exploiting the mutual coupling. In respects of channel capacity, to consider the mutual coupling, we modified channel matrix. We calculated the channel capacity in single−input multiple−out systems, and the coupled case and uncoupled case of channel capacity were compared. Our results show that the channel capacities of the coupled and uncoupled case are converged because the impact of mutual coupling decreases as the spacing of antennas is larger. Since the received power and channel capacity are different depending the spacing of antenna, the interval of antenna have to be decided according to the situation that what's the performance among them is required further more than. To solve these problems, the optimization modeling is suggested.

As the effect of mutual coupling phenomena between dipole antennas is proved in this paper, generalization of the mutual coupling effect, given here based on theoretical analysis and simulation results, should be proved by experiments in future work. In addition, since mutual impedance calculated in previous works [7]−[8] is mainly for dipole antennas, further research is required to generalize over other types of antennas, such as slot and patch antennas. Also, the performance of SWIPT in the fading channel will be focused.

References

[1] Z. Ding, C. Zhong, D. Wing Kwan Ng, M. Peng, H. Suraweera, R. Schober, and H. V. Poor, "Application of smart antenna technologies in simultaneous wireless information and power transfer," *Communications Magazine, IEEE,* vol. 53, no. 4, pp. 86-93, 2015.

[2] L. R. Varshney, "Transporting information and energy simultaneously." pp. 1612-1616.

[3] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," Communications, IEEE Transactions on, vol. 61, no. 11, pp. 4754-4767, 2013.

[4] L. Liu, R. Zhang, and K.-C. Chua, "Wireless information transfer with opportunistic energy harvesting," Wireless Communications, IEEE Transactions on, vol. 12, no. 1, pp. 288-300, 2013.

[5] G. Cohn, S. Gupta, T.-J. Lee, D. Morris, J. R. Smith, M. S. Reynolds, D. S. Tan, and S. N. Patel, "An ultra-low-power human body motion sensor using static electric field sensing." pp. 99-102.

[6] K. Souri, and K. Makinwa, "A 0.12 mm2 7.4 μW Micropower Temperature Sensor With an Inaccuracy of±0.2 °C (3σ) From-30 °C to 125 °C," IEEE J. Solid-State Circuits, vol. 46, no. 7, pp. 1693-1700, 2005.

[7] C. A. Balanis, Antenna theory: analysis and design: John Wiley & Sons, 2005.

[8] H. T. Hui, "A new definition of mutual impedance for application in dipole receiving antenna arrays," Antennas and Wireless Propagation Letters, IEEE, vol. 3, no. 1, pp. 364-367, 2004.

[9] J. W. Wallace, and M. Jensen, "The capacity of MIMO wireless systems with mutual coupling." pp. 696-700.

[10] J. Zhang, Y. Huang, and P. Cao, "Harvesting RF energy with rectenna arrays." pp. 365-367.

[11] U. Olgun, C.-C. Chen, and J. Volakis, "Design of an efficient ambient WiFi energy harvesting system," IET Microwaves, Antennas & Propagation, vol. 6, no. 11, pp. 1200-1206, 2012.

[12] W. H. Hayt, and J. A. Buck, Engineering electromagnetics: McGraw-Hill New York, 2001.

[13] T. Svantesson, and A. Ranheim, "Mutual coupling effects on the capacity of multielement antenna systems." pp. 2485-2488.

[14] D.-w. Seo, and N.-H. Myung, "Analysis of mutual coupling effects on channel capacity of Rician MIMO channel." pp. 1-4.

[15] H. T. Hui, W. O. Yong, and K. Toh, "Signal correlation between two normal-mode helical antennas for diversity reception in a multipath environment," Antennas and Propagation, IEEE Transactions on, vol. 52, no. 2, pp. 572-577, 2004.

[16] D. Tse, and P. Viswanath, Fundamentals of wireless communication: Cambridge university press, 2005.

[17] T. Su, and H. Ling, "On modeling mutual coupling in antenna arrays using the coupling matrix," Microwave and Optical Technology Letters, vol. 28, no. 4, pp. 231-237, 2001.

[18] H.-S. Lui, H. T. Hui, and M. S. Leong, "A note on the mutual-coupling problems in transmitting and receiving antenna arrays," Antennas and Propagation Magazine, IEEE, vol. 51, no. 5, pp. 171-176, 2009.

[19] J. R. Hampton, Introduction to MIMO Communications: Cambridge University Press, 2013.

[20] S. Boyd, and L. Vandenberghe, Convex optimization: Cambridge university press, 2004.

요 약 문

안테나간 상호결합 현상이 무선 정보 및 전력 동시 전송 시스템 성능에 미치는 영향에 관한 연구

사물 인터넷을 구현하는데 있어서 큰 문제점 중 하나로 센서 노드의 제한된 베터리 용량 문제가 있으며 이 문제를 해결하기 위한 방안 중 하나로 무선 정보 및 전력 동시 전송기법(simultaneous wireless information and power transfer, SWIPT)이 있다. SWIPT는 안테나로부터 수신된 전자기파를 상황에 따라 통신용으로 사용하거나 혹은 에너지 수확용으로 사용하는 기술이다. 하지만, 단일 안테나를 이용해서 수확한 에너지는 센서 노드의 베터리를 충전하기 위해 필요한 에너지보다 작기 때문에 여러 안테나를 배열하여 총 수확 에너지를 올려야 한다. 그런데, 여러 안테나를 배열하게 되면 안테나간 전자기적인 결합 현상인 상호결합현상이 발생하게 되며 이 현상은 SWIPT 성능에 영향을 끼치게 된다. 본 논문에서는 안테나간 상호결합현상이 SWIPT 성능 지표인 에너지 수확량과 채널용량에 끼치는 영향에 관해 분석하였다. 안테나간 상호결합현상은 배열된 안테나 수와 안테나 사이의 거리에 따라 달리 지게 되므로 배열된 안테나 수와 안테나 거리에 따른 에너지 수확량과 채널용량을 시뮬레이션을 통해 검증하였으며 에너지 수확량과 채널용량 중 우선시 되어야 하는 성능을 올리기 위해 최적화 문제를 모델링 하였다.

핵심어: SWIPT, 상호결합, 상호 임피던스, RF 에너지 수확, SIMO 시스템 채널용량

감사의 글

2014년 대구경북과학기술원 정보통신융합공학전공 석사과정에 입학하여 어느덧 졸업을 앞두게 되었습니다. 미흡하지만 학위 논문을 마치면서 석사학위기간 동안 도움을 주신 분들께 감사의 마음을 전하고자 합니다.

먼저 항상 저를 응원해주시고 큰 버팀목이 되어주시는 부모님께 감사의 마음을 전합니다. 부모님으로부터 배운 배려심과 감사하는 습관은 대학원 생활뿐만 아니라 인생을 살아가는데 있어서 아주 큰 도움이 되었습니다. 그리고 부족한 저를 지도해주신 최지환 교수님께 감사드립니다. 교수님의 가르침을 통해서 연구활동뿐만 아니라 겸손과 협동심 등 공학도가 가져야 할 기본소양을 갖추게 되었습니다. 또한 함께 지도해주신 최지웅 교수님과 장재은 교수님께도 감사드립니다. 교수님들의 지도 덕분에 2년 동안 진행한 연구가 좋은 결실을 맺을 수 있었습니다.

그리고 2년동안 디지스트 생활을 함께 한 14학번 동기 고병진, 곽초록, 김경복, 김세웅, 김소라, 류민규, 송영욱, 원유창, 윤세효, 이경화, 이태주, 이홍재, 임성호, 임희성, 정혜림, 조승익, 박진만, 최기훈, 한동형에게도 감사합니다. 입학 전 영어프로그램, 교내 워크숍준비, 동기모임, ICE 피크닉, DGIF, 비슬산 등산 등 동기들과 함께하였기에 즐겁게 보낼 수 있었습니다. 그리고 우리 연구실 든든한 랩장 종엽이형과 진심 어린 조언을 해주신 한준이형 운동의 길을 열어준 용화형에게도 감사합니다.

또한, 항상 나의 어려움을 들어주고 힘이 되어주는 내 친구들에게도 감사합니다. 재혁이 아빠 영석이, 야근에 찌든 효진이, 제일 잘생긴 민식이, 류준열 닮은 형욱이, 이성에게 인기가 제일 많은 승우, 주량이 아쉬운 대성이 그리고 나보다 더 시커먼 동환이에게도 감사합니다.

마지막으로 부모님 못지않게 큰 도움이 되어준 우리 미선이 고모, 고모부, 서영이, 서준이, 준형이 형, 동생 슬아랑 대박이에게도 감사의 마음을 전합니다.

이렇게 많은 분들의 도움으로 이 논문을 완성할 수 있었고 이러한 도움이 더욱 빛나도록 앞으로도 최선을 다하겠습니다. 다시 한 번 진심으로 감사합니다.