An Investigation of a Wearable Antenna Using Human Body Modelling

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Abstract **─** The work presented is an assay done on the effects of wearable antenna when placed in proximity to the human body. Cloth fabric is used as a substrate to design a planar antenna. Measurement results of the fabricated patch at free space and close to the human body are also presented here. The S_{11} of the designed antenna when placed close to the body tissue is almost -30 dB and the gain is close to 4 dB. A rectangular three layered human body model is used to evaluate the extent of the effect that the human body has on the parameters that define an antenna like its gain, directivity, etc.

Index Terms **─** Fabric substrate, Specific Absorption Rate (SAR), Wearable Antenna.

I. INTRODUCTION

The use of fabric as a substrate material for antennas has gained recent notice. Using the fabric in such a manner would provide the much pursued integration of antenna with clothing. To this end, a study on the effect of the human body on a simple patch, fabricated on a jean cloth is presented here. The results analyzed in this paper would aid in designing textile antennas, giving the best possible position on the human body without compromise on its performance.

Bending characteristics of antenna on a flexible substrate of a simple wearable antenna was previously analyzed [1]. The effect of varying distance of wearable antenna from the human body on the antenna parameters has also been done [2]. The use of wearable antenna for the purpose of medical monitoring has also been studied recently. The challenge of designing wearable antennas is still high and a surprising interest in the area has been noticed in recent months. A button wearable antenna and an L shape Planar Inverted F Antenna (PIFA) have been designed for medical e-Health system [3]. An Ultra-Wideband (UWB) printed antenna for wearable applications to monitor cardiac activity has been reported [4].

In another design for medical application wearable antenna that can be integrated with EKG sensors have been proposed [5]. The effect of ground plane on the efficiency of a wearable antenna is studied in [6], while [7] examines the effect of varying textiles on the antenna's performance. Analysis on the effect of bending on a wearable dipole patch is done in [8]. Research on the study of the feasibility and reliability of wearable antennas is still underway.

According to [9], "characterization of antennas is the key to establishing reliable on-body data transmission between sensors and the main data-collecting node (this may be worn on-body or an external stationary or mobile unit)." Hence, there is an immense need for characterizing the antenna and its performance when in the vicinity of the human body so that it can be used for wearable applications.

This paper puts forward a clear evaluation of the effect of the human body on the parameters that define an antenna. In order to design an on-

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body wearable antenna, a fabric whose permittivity is known, can be used as the substrate material.

Major attraction of these wearable antennas would be its use in defense. It would serve to reduce to a great extent, the paraphernalia carried by soldiers, thus improving mobility of the troop. The implementation of wearable antennas can also provide medical monitoring of patients with chronic illness as they go about their daily chores. It could also be tweaked to help monitor patients with psychological disorders. Antenna if integrated onto the clothing of an individual would provide unrestricted movement and obviate the need to carry around large antenna.

II. WEARABLE PATCH DESIGN

A simple rectangular patch was designed for an operating frequency of 2.45 GHz using the transmission line model equations [10]. The height of the substrate is taken as 1 mm (normal thickness of jean fabric). The relative permittivity of the jean fabric at 2.45 GHz is 1.67 and permeability of 1.

Dimensions calculated according to the transmission line model [10]: length of the patch is 44.35 mm, width is 53 mm. The patch excited by a 50 Ω transmission line of length λ/4. Jean fabric that is 1 mm thick is used as the substrate. A square 120 x 120 mm^2 ground plane made of copper is also used for this design. The thickness of the ground plane and the patch is 0.035 mm. The antenna is simulated using CST Microwave Studio. The snapshot of the designed antenna is given in Fig. 1.

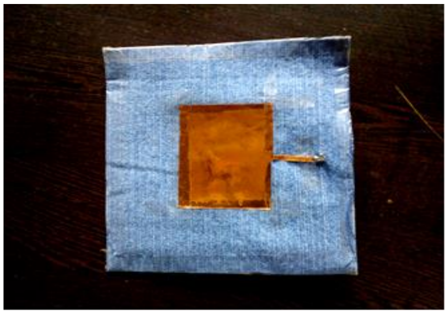


Fig. 1. A wearable patch antenna designed on a jean cloth fabric and excited by a transmission line feed.

A parametric sweep reveals that for different values of denim as found from literature, there is little variation in the frequency of patch with only a slight mismatch occurring due to the dimensions of the patch, and the feed point kept constant. Hence, we have chosen 1.67 as the dielectric constant in our study. Agilent Vector Network Analyser was used for the measurement of return loss of the antenna in free space. Measurement setup for the wearable antenna is shown in Fig. 2.

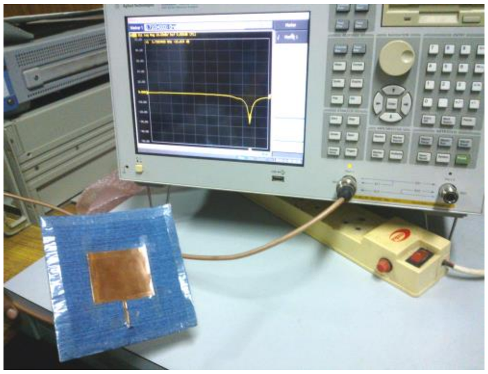


Fig. 2. The measurement setup for measurement of antenna parameter in free space.

Results obtained from measurement are compared to those obtained through simulation in Fig. 3. A slight shift in frequency in the simulated and measured results of the return loss of the antenna when placed in free space is observed. Utilizing accurate and appropriate fabrication methods, the deviation in the frequency could be reduced to a great extent. However, there is a good agreement in the return loss of the patch simulated and measured, which is observed to be 20.62 dB during simulation and 20.9 dB when measured.

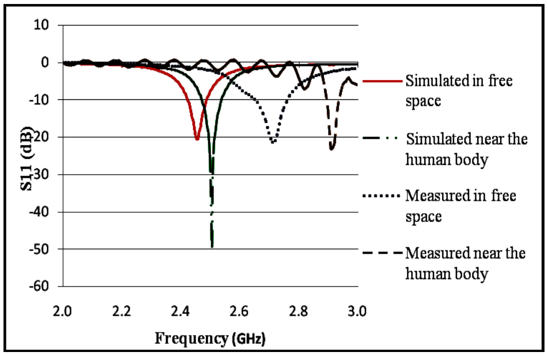


Fig. 3. The plot of S_{11} versus frequency for the designed wearable antenna, near and away from the human body.

By the use of better-suited fabrication methods, exact performance can easily be obtained. This is an issue that would require further improvement. The actual dimension of the patch length measured is approximately 40.1 mm, which when simulated shows a resonant frequency of 2.697 GHz while measured is at 2.72 GHz. Figure 4 shows the simulated radiation pattern in the vicinity of the body model.

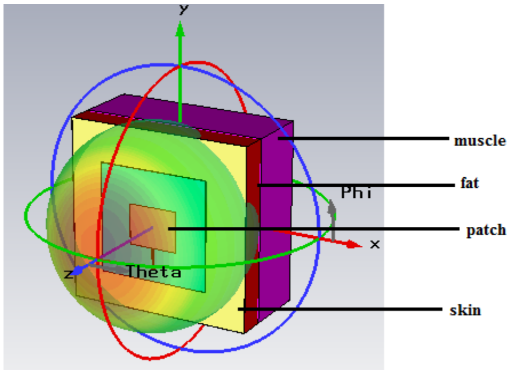


Fig. 4. Simulated radiation pattern in the vicinity of the body model.

III. SAR ASSESSMENT AND BODY EFFECTS DUE TO WEARABLE ANTENNA

A. Human body modelling

Since the application of wearable antennas necessitates it to function in close proximity to the human body, we need to assess the parameter changes in the antenna when working in such an environment [11]. To find the amount of electromagnetic radiation captured by the tissues in the body, evaluation of the Specific Absorption Rate (SAR) becomes necessary. SAR is a measure of the rate at which energy is absorbed by the body when exposed to the Radio Frequency (RF) electromagnetic field. It can also refer to the absorption of other forms of energy by tissue, including ultrasound. It is expressed as the power absorbed per mass of tissue and has units of Watts per Kilogram (W/Kg). SAR is usually averaged either over the whole body or over a small sample volume (typically 1 gram or 10 grams of tissue).

SAR can be calculated from the electric field within the tissue as:

$$\mathrm{SAR} = \int \left(\frac{\left(\sigma(r) |E(r)|^2 \right)}{\rho(r)} \right) dr , \qquad (1)$$

where σ (r) - Sample Electrical Conductivity, E - RMS Electric Field, and ρ (r) - Sample Density. SAR is directly proportional to the conductivity of the tissue absorbing the radiation and inversely proportional to its density. The maximum permissible value for SAR is 1.6 W/Kg.

Hence, a broad analysis on the Specific Absorption Rate has been done for varying distance of the antenna from the body. The readings are noted with respect to the wavelength of operation in order to better understand the analysis done.

In order to assess the SAR for varying distance we need to define body models that would replicate the presence of lossy tissue close to the antenna. Usually detailed body models, those including organs, are complicated and demands more run time while utilizing resource intensively.

In literature, there are simplified human body models like the lossy cylinder with defined dielectric constant and conductivity and the rectangular body model [12]. The rectangular model of body is chosen for our study since it was found to give excellent agreement with measurements.

In the rectangular three layered model we have considered thickness of skin is taken as 0.4 mm, thickness of fat as 30 mm, and that of muscle is 69.6 mm. The permittivity, loss tangent and density for the different tissues are as follows. Skin: εr=37.952, δ=0.28184 and density is 1050kg/m3. Fat: εr=5.2749, δ=0.14547 and density is 918kg/m3. Muscle: εr=52.73, density is 1100kg/m3. All these parameters have been defined at frequency 2.45 GHz, according to [13].

Mass averaged Specific Absorption Rate, SAR (10 g) is estimated for distances varying from 0 λ to 0.08 λ between the body tissues and the antenna. In order to fully comprehend this, defining the quantity obtained as SAR becomes necessary.

Specific absorption rate or SAR is the amount of electromagnetic radiation absorbed by the body tissues. The sample volume considered for calculation of SAR can be 1 g or 10 g. 10 g sample is appropriate for our study when considering body regions like chest, wais, etc., that would generally be the positions of these wearable antennas. SAR depends on the conductivity and density of the sample considered.

B. Analysis of the effect of the human body on the antenna

Using the rectangular human body model explained in the previous section, we perform the following analysis. To learn about the effects of the body on the antenna [14], the S_{11} variation with respect to the frequency is studied. As can be seen from the graph of the simulated S_{11} versus frequency, when the antenna is placed on the human body it experiences a frequency shift of 48 MHz from 2.457 GHz to 2.505 GHz, as shown in Fig. 3.

The measurement of the return loss of the antenna is also done by placing the antenna on the body, as shown in Fig. 5. This measurement again shows a resonant frequency shift of 190 MHz from 2.72 GHz to 2.91 GHz when the antenna is placed in the vicinity of the human body. The reason for this shift in the resonant frequency is because of the dielectric loading due to the lossy human tissue [15] which is in close proximity to the wearable patch antenna.

When kept at free space, the simulated resonant frequency was at 2.457 GHz. The gain was observed as 4.144 dB and directivity of 8.957 dBi. The variation of SAR, gain, impedance and directivity are also analyzed from simulation with varying distance from the body in terms of wavelength, as presented in Table 1. Figure 6 depicts the simulation results of SAR for varying body-antenna separation.

Another analysis, keeping the over-all thickness as 100 mm and varying the depth of each layer is presented in Table 2. Most of the areas necessitating wearable antennas would be requiring the use of antenna arrays. A 1 x 4 array was constructed and simulations were run for various layer thickness. The values are noted in Table 3.

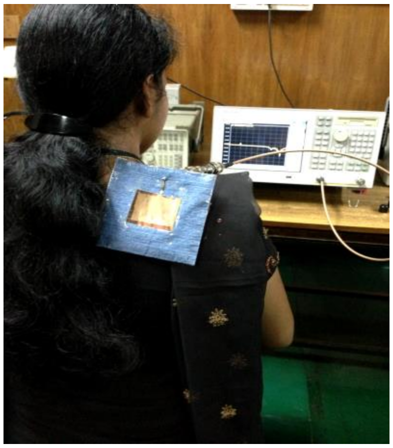
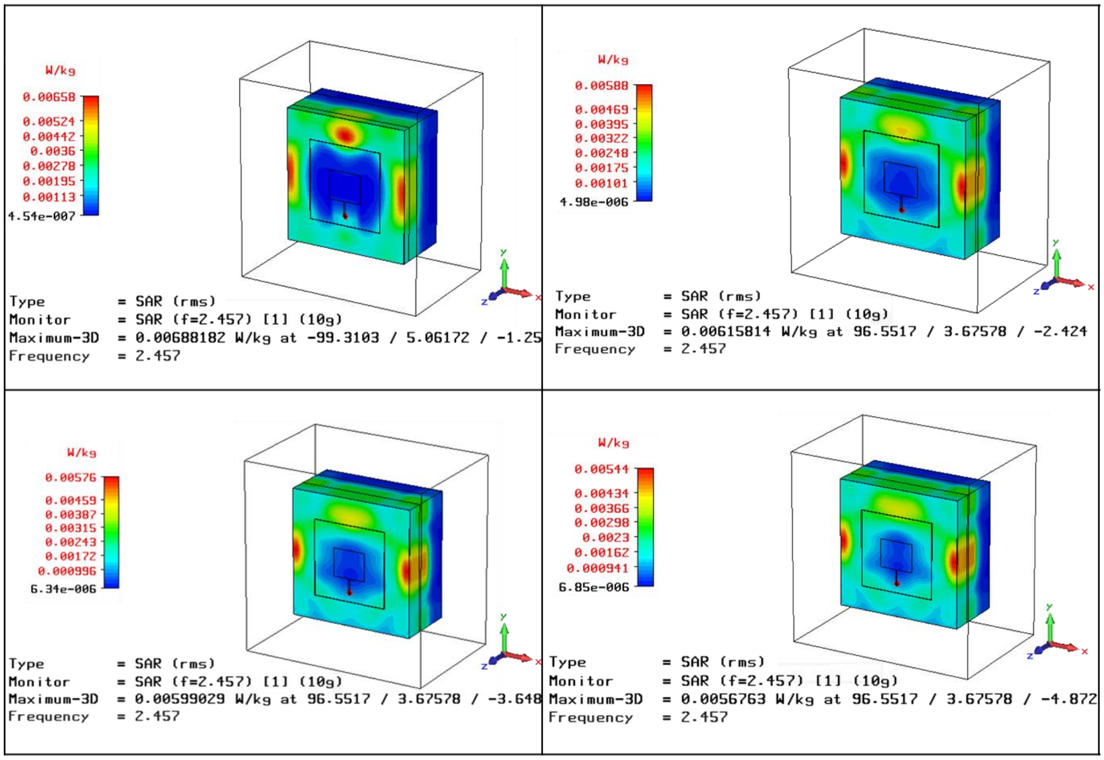


Fig. 5. Return loss measurement for antenna placed on-body.

Table 1: Table depicting the antenna parameters and SAR values for varying distance of the antenna from the body

Distance of Separation	Input Impedance (ohms)	Gain (dB)	Directivity (dBi)	SAR (W/Kg)
0λ	53.77, 0.27	3.956	8.682	0.00626
0.01λ	53.80, 0.24	3.932	8.680	0.00625
0.02λ	53.79, 0.23	3.932	8.677	0.00618
0.03λ	53.79, 0.22	3.922	8.666	0.00595
0.04λ	53.74, 0.34	3.908	8.651	0.00561
0.05λ	53.73, 0.35	3.898	8.641	0.00437
0.06λ	53.73, 0.35	3.884	8.627	0.00488
0.07λ	53.78, 0.24	3.887	8.626	0.00455



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Type        = SAR (rms)
Monitor     = SAR (f=2.457) [1] (10g)
Maximum-3D  = 0.00688182 W/kg at -99.3103 / 5.06172 / -1.25
Frequency   = 2.457
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```
Type        = SAR (rms)
Monitor     = SAR (f=2.457) [1] (10g)
Maximum-3D  = 0.00615814 W/kg at 96.5517 / 3.67578 / -2.424
Frequency   = 2.457
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```
Type        = SAR (rms)
Monitor     = SAR (f=2.457) [1] (10g)
Maximum-3D  = 0.00599029 W/kg at 96.5517 / 3.67578 / -3.648
Frequency   = 2.457
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```
Type        = SAR (rms)
Monitor     = SAR (f=2.457) [1] (10g)
Maximum-3D  = 0.0056763 W/kg at 96.5517 / 3.67578 / -4.872
Frequency   = 2.457
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Fig. 6. Simulated SAR distribution for varying distances of the antenna from the body; 0λ, 0.01 λ, 0.02λ, and 0.03λ.

Table 2: Table depicting the parameter changes in an antenna and SAR values for varying thickness of individual layers

Varying Thickness (mm)			Input Impedance (ohms)	Gain (dB)	Directivity (dBi)	SAR (W/Kg)
Skin	Fat	Muscle				
0.4	0	99.6	53.90, 0.26	3.740	8.458	0.00659
0.4	15	84.6	53.73, 0.36	4.541	9.305	0.01005
0.4	30	69.6	53.80, 0.24	3.932	8.680	0.00625
2.6	0	97.4	53.88, 0.25	3.748	8.471	0.00669
2.6	15	82.4	53.82, 0.43	3.689	8.423	0.00831
2.6	30	67.4	53.87, 0.30	3.871	8.597	0.00719

Table 3: Table depicting the parameter changes in a 1 x 4 antenna array and SAR values for varying thickness of individual layers

Varying Thickness (mm)			Gain (dB)	Directivity (dBi)	SAR (W/Kg)
Skin	Fat	Muscle			
0.4	0	99.6	6.461	14.04	1.23789e-006
0.4	15	84.6	6.421	14.01	9.64977e-007
0.4	30	69.6	6.394	13.97	2.67269e-007
2.6	0	97.4	6.365	13.96	3.02758e-007
2.6	15	82.4	6.392	13.96	9.12359e-007
2.6	30	67.4	7.179	13.75	1.64409e-006

The frequency is at 2.505 GHz when in the vicinity of the human body, but does not show variation with respect to the distance since it is in the radiative far field of the patch. The foremost observation made from this specific study is the variation or the lack of it in the input impedance, gain and directivity for different distances from the body. Extensive literature study reveals the reason as: the boundary for the far-field region of a patch is normally so small that it would lie within the ground plane itself [16]. When the human body is near the antenna and absorbs power from the near field. By altering the reactive near field, the body affects the input impedance and other antenna parameters. In literature, as cited in [16], microstrip antennas near field maximum occurs in the gap between the element and the ground plane and the reactive near field is negligible elsewhere. Hence, the reactive near field region in microstrip antennas is much smaller than $\lambda/2\pi$.

Also, the percentage detuning by the human body given by (100*detuning)/free space frequency is 1.95 % for all distances simulated. The dielectric constant and penetration depth in the body is different for different frequencies. Hence, the detuning varies with the frequency. If we can design an antenna with a broadband characteristic such that the -10 dB impedance bandwidth encompasses the shifted frequency, the design would be acceptable. Literature has it that [16] dipoles as well as antennas working at lower frequencies have a very large percentage of detuning than microstrip antennas. This point would allow us to draw the conclusion that a patch antenna structure would be the best suitable contender for on-body wearable antennas. PIFA antennas also have a small far field, but considering the fabrication possibilities, a microstrip patch antenna scores over it with several distinct advantages. It does not require shorting, which makes its fabrication on the textile easier.

The second analysis will throw light on how different parts of the body, say, limbs, torso, etc., will impact the antenna parameters. The variation of SAR for different layer depths presents an interesting phenomenon that for a particular thickness of fat, say 15 mm, the SAR value slightly increases. A region in the human body with very less amount of fat is the best position for the placement of a wearable antenna. Say, when a jacket has a wearable antenna array, the antenna could be fabricated such that it lies at the back of the torso of the human body so that lesser radiation absorption takes place. These analyses throw light on the placement and positioning of wearable antennas when they are modeled for any particular application.

Similarly, simulation results as noted in the third analysis have revealed that for array antennas the SAR has decreased to a great extent. In an array as the pattern becomes more directive [17] and points away from the body when compared to a single patch, the SAR decreases. Hence, the conclusions drawn from this study and the insight gained can be used when larger more complicated arrays are designed.

VI. CONCLUSION

A comprehensive investigative study on the working of wearable antennas has been projected in this paper. Real time examination of the results has been demonstrated by the fabrication of a patch antenna integrated into cloth fabric.

Extensive analysis on both the effects of the antenna on the body and the effects of the human body on the antenna has been presented in detail.

REFERENCES

[1] S. Sankaralingam and B. Gupta, "Determination of dielectric constant of fabric materials and their use as substrates for design and development of antennas for wearable applications," *IEEE Transactions on Instrumentation and Measurement*, vol. 59, no. 12, December 2010.

[2] A. Alomainy, Y. Hao, and D. M. Davenport, "Parametric study of wearable antennas with varying distances from the body and different on-body positions," *2007 IET Seminar on Antennas and Propagation for Body-Centric Wireless Communications*, pp. 84-89, April 2007.

[3] W. Huang and A. A. Kishk, "Compact antenna designs for wearable and medical portable systems," *ACES Journal*, vol. 26, no. 4, April 2011.

[4] E. Pittella, P. Bernardi, M. Cavagnaro, S. Pisa, and E. Piuzzi, "Design of UWB antennas to monitor cardiac activity," *ACES Journal*, vol. 26, no. 4, April 2011.

[5] C. Kruesi, L. Yang, D. Staiculescu, M. M. Tentzeris, and M. Phelps, "Reusable wearable patch antenna for health monitoring body area sensor network," *25th Annual Review of Progress*

in Applied Computational Electromagnetics, March 8-12, 2009.

[6] H. Giddens, D. L. Paul, G. S. Hilton, and J. P. McGeehan, "Influence of body proximity on the efficiency of a wearable textile patch antenna," *6th European Conference on Antennas and Propagation (EUCAP)*, 2011.

[7] S. Sankaralingam, S. Dhar, and B. Gupta, "Preliminary studies on performance of a 2.45 GHz wearable antenna in the vicinity of human body," *2012 International Conference on Communications, Devices and Intelligent Systems (CODIS)*, pp. 250,253, December 28-29, 2012.

[8] N. A. Elias, N. A. Samsuri, M. K. A. Rahim, and N. Othman, "The effects of human body and bending on dipole textile antenna performance and SAR," *Proceedings of APMC 2012*, December 4-7, 2012.

[9] T. Yilmaz, R. Foster, and Y. Hao, "Detecting vital signs with wearable wireless sensors," *Sensors*, vol. 10, pp. 10837-10862, 2010.

[10] C. A. Balanis, "Antenna theory, analysis and design," *John-Wiley and Sons Inc.*, New York, 1997.

[11] M. A. R. Osman, M. K. A. Rahim, M. Azfar, N. A. Samsuri, F. Zubir, and K. Kamardin, "Design, implementation and performance of ultra-wideband textile antenna," *Progress In Electromagnetics Research B*, vol. 27, pp. 307-325, 2011.

[12] K. E. Wasife, "Power density and SAR in multi-layered life tissue at global system mobile (GSM) frequencies," *Journal of Electromagnetic Analysis and Applications*, vol. 3, pp. 328-332, 2011.

[13] P. S. Hall and Y. Hao, "Antennas and propagation for body-centric wireless communications," *Artech House*, Norwood, 2012.

[14] M. A. R. Osman, M. K. A. Rahim, N. A. Samsuri, H. A. M. Salim, and M. F. Ali, "Embroidered fully textile wearable antenna for medical monitoring applications," *Progress In Electromagnetics Research*, vol. 117, pp. 321-337, 2011.

[15] G. Emili and A. Schiavoni, "Computation of electromagnetic field inside a tissue at mobile communications frequencies," *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, no. 1, pp. 178-186, 2003.

[16] T. Kellomaki, J. Heikkinen, and M. Kivikoski, "One layer GPS antennas perform well near a human body," *Proc. European Conference of Antennas and Propagation*, UK, November 2007.

[17] Y. Huang and K. Boyle, "Antennas from theory to practice," *Wiley Publishers*, 2008.

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