**Paper:**

Mehta, A. (in press). Conformal Beam-steering Antenna Integrated with Raspberry Pi for Sustained High Throughput Applications. *IEEE Transactions on antenna and propagation*

Accepted with corrections: 18th April 2017, IEEE Transactions on antenna and propagation

# Conformal Beam-steering Antenna Integrated with Raspberry Pi for Sustained High Throughput Applications

Arpan Pal, *Member, IEEE*, Amit Mehta, *Senior Member, IEEE*, Hasanga Goonesinghe, Dariush Mirshekar-Syahkal, *Fellow IEEE* and Hisamatsu Nakano, *Life Fellow, IEEE*

***Abstract*— A complete system consisting of a conformal beam steerable Hemispherical Square Loop Antenna (HSLA) integrated with a Raspberry Pi is presented for optimizing the spectrum efficiency in a rough ElectroMagnetic (EM) environment. It is demonstrated that in a weak EM environment (signal close to the noise floor) the HSLA enables a throughput increment by a factor over 100 (0 to 7.7 Mbps). In quality terms this means sustaining full HD communications. In effect it improves the system spectrum efficiency for the test 2.4 GHz (802.11b/g/n) WiFi band. Automatic pattern adaption is achieved using a smart 'EM sense, scan, analyze and lock' algorithm running on Raspberry Pi. The Pi tracks the direction of signal arrival for the highest RSSI (Received Signal Strength Indicator). The Pi algorithm controls the radiation from the HSLA in one of the four possible tilted beam directions by utilizing a RF SP4T switch. The uniqueness about the system is that it only uses single antenna for both sensing and communication. The algorithm works at application layer that controls the RF switch and antenna patterns at physical layer. Thus, the entire middle protocol layers are untouched. The system can easily be retrofitted to existing non-adaptive communication systems.**

***Index Terms*—Adaptive beam steering, High definition video, Impedance matching, Raspberry Pi, Square loop antenna, High throughput communications.**

## I. Introduction

WITH the growing demand for high-throughput wireless communications with ubiquitous coverage is enabling arrival of the new antenna technology. A special aspect of future high speed internet access has to be on the high quality video transmissions. Over next three years 2/3 of the wireless traffic will be video [1]-[2], such as High Definition (HD) video conferencing [3], video on demand, MobiTv [4], electronic classroom [5] and WiFi telecast in smart homes [6].

A. Pal, A. Mehta and H. Goonesinghe are with College of Engineering, Swansea University, Swansea, SA28PP, U.K. (email: a.pal@swansea.ac.uk, a.mehta@swansea.ac.uk, 668590@swansea.ac.uk ).

D. Mirshekar-Syahkal is with the Department of Computing Science and Electronic Engineering, Essex University, Colchester, Essex CO4 3SQ, U.K. (e-mail: dariush@essex.ac.uk).

H. Nakano is with the Science and Engineering Department, Hosei University, Koganei, Tokyo 184-8584, Japan (e-mail: hymat@hosei.ac.jp).

With the new extended bandwidth allocation in 5G a multi-gigabit / sec data speed will be realizable [7]-[8]. However, those speeds will only work in areas with a high SIR (Signal to Interference Ratio). In situation of a device operating in a weak ElectroMagnetic (EM) environment, e.g. away from the base stations or in a rich multipath or in a high interference zone the data rates will drop sharply, in line with the Shannon capacity [9]. These low SIR operating conditions will degrade the user experience and expectations. One clever way to solve this degradation is to use high gain beam-steering antennas. The high gain will increase a wireless device received power. Beam-steering would enable the device to navigate away from interferences and noise. Both together will push up the effective SIR and in turn the spectrum capacity [10]-[12].

In this paper we demonstrate using a real world example with throughput numbers on how in weak EM environment beam-steering antenna can make significant difference. In fact, by over a factor of 100. We achieve this by designing and practically implementing a low cost high gain intelligent beam steering antenna system. We used off-the shelves components to ensure compliance with future consumer wireless systems. We choose 2.45 GHz as the test frequency and OFDM WiFi as test protocol. This choice was underpinned with it being a high throughput mature technology from of-the shelves perspective and that it also scales gracefully to both higher and lower frequency spectrum.

For beam-steering antenna we selected single element four feed based Square Loop Antenna (SLA). It is similar to [13]-[18], but is the first SLA developed on a hemispherical platform. An important aspect of future communications would be high speed connected cars. We selected full hemispherical conformal shape to ensure that our system would easily adapt to various vehicular top and side platforms. In addition, the conform shape is relevant for implementation in the future technologies (e.g. Internet of Things) in which wireless sensors platforms would be of random shapes. The antenna radiates four 9.2 dBi gain tilted beams in a 90° azimuth space (single quadrant), one corresponding for each of the feeds. Using a Single Pole Four Throw (SP4T) RF switch [19] the antenna is capable of switching feeds sequentially one at a time and that it can steer a high gain beam in the full 360° azimuth space. Whilst we could have used phased arrays for beam-steering, that choice would have been expensive, lossy and importantly it would have required large space area for incorporating multiple antenna elements [20]-[23]. The intelligence for beam steering was done with the help of Raspberry Pi2 model B [24]. Pi provides control signals for controlling the RF switch. A smart 'Electromagnetic sense, Analyze and Lock' algorithm was developed using C language which sits on the Pi. The algorithm enables antenna to ensure that the communication link is always locked in the strongest SIR / RSSI (Receive Signal Strength Indicator) direction. Using a full High Definition (HD) video internet networking we demonstrated the effectiveness of the pattern adaptive system in sustaining the uninterrupted quality video. We demonstrated that in that weak signal environment a high gain beam-steering was the difference between full HD communication and no communication at all.

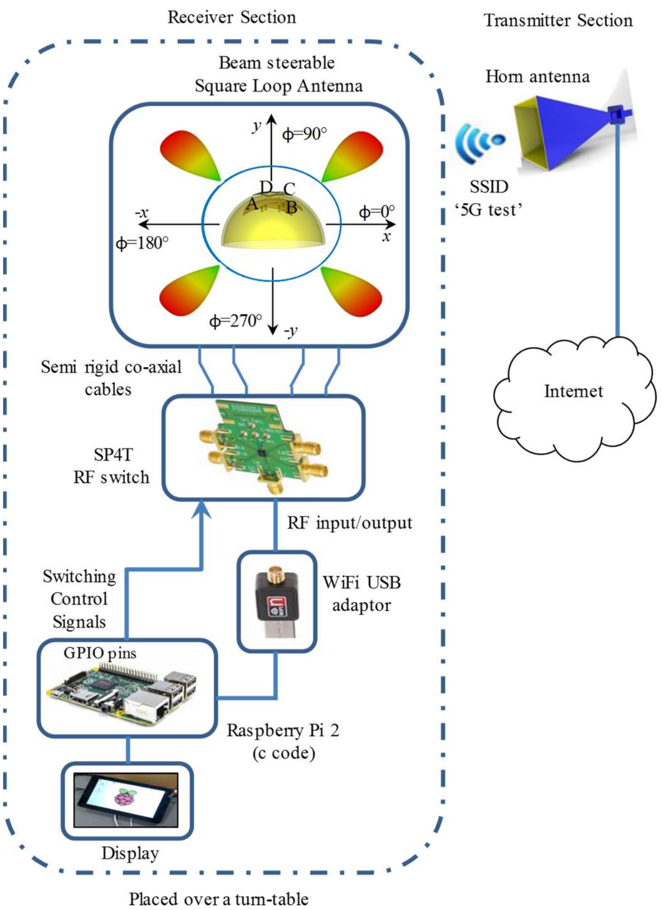
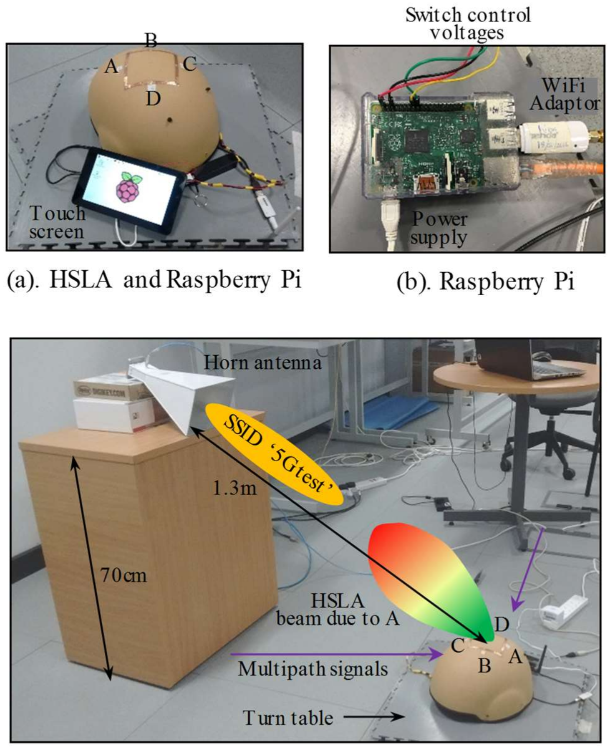



Fig. 1. Schematic of the beam-steering system.

## II. Experimental set-up

Fig. 1 shows the complete configuration of the implemented beam-steering system. The transmitter is a horn antenna connected to the internet via a cisco router [25]. The horn antenna provides a direct WiFi link to the receiver section and is placed on a wooden platform having a height of 70cm, Fig 2. The line of sight distance between HSLA and horn was 1.3 meters in the far field region.

The receiver section consists of a conformal beam-steering Hemispherical Square Loop Antenna (HSLA) integrated with a SP4T RF switch and a single board computer - Raspberry Pi. The Pi unit is attached behind a 7" touchscreen display which is powered by a USB (Universal Synchronous Bus) battery (Fig. 2 a). The whole receiver section is placed on a turn table. For experimental purpose a near hemispherical Kevlar helmet was used as a substrate for the SLA.




(a). HSLA and Raspberry Pi (b). Raspberry Pi

(c). Experimental set-up

Fig. 2. Experimental set-up including (a) HSLA, (b) controller (Pi) and (c) test environment.

The proposed system is designed to operate over 2.4 GHz (802.11b/g/n) WiFi band. Center frequency of this band (2.4 to 2.5 GHz) is 2.45 GHz and it is selected as the test frequency throughout this paper. Pi was provided the WiFi functionality using a USB based WiFi transceiver [26]. The Omni-antenna for that transceiver was removed and the transceiver was directly connected to the SP4T RF switch. The switch then connects the transceiver to one of the four possible antenna ports. Based on which port was selected the antenna radiated a beam in one of the four possible spatial azimuth directions, as shown in Fig. 1.

## III. Hemispherical Square Loop Antenna (HSLA)

Fig. 3 shows the transition of Planar SLA (PSLA) to Hemispherical SLA (HSLA). Fig 3 (a) shows the top and side view of the PSLA on a circular substrate. The square loop is placed on top of a circular substrate having a radius of 247mm (horizontal radius, $r_h$). The antenna substrate consists of a stack of two dielectric layers. The dielectric material Kevlar

($\varepsilon_r$ =3.4) is used as top layer which has a height of $h_1$=8.45mm. The bottom layer has a height $h_2$ =14mm and is made of Rohacell 51 foam ($\varepsilon_r$ =1.08). Hence, the total height of the antenna is 22.5mm. The radiating square loop is composed of four copper strips having a length $l$=96mm and a track width $w$=5 mm. The loop is excited at four middle points (A, B, C and D) of the four arms by four vertical probes having a diameter of 1.3mm. The probes are connected to the four standard SMA (*SubMiniature version A)* ports $A_0$, $B_0$, $C_0$ and $D_0$, respectively at the bottom of ground plane. The square shaped metallic (Copper) ground plane has an area of 175mm×175mm and it is rotated by 45° in the *xy*-plane with respect to the square loop. Fig. 3 (b) shows the PSLA conformed to HSLA. This was achieved by bending the PSLA from sides in which the middle portion of the ground plane along with substrate, feeds and square loop are raised. To keep the constant surface area, the bending caused reduction in horizontal radius $r_h$=175mm, an increase in vertical radius $r_v$=175mm, and a stretching of the ground plane (180.2mm×180.2mm). The length of each strips of square loop only increased by 0.3 mm in the PSLA to HSLA transition.

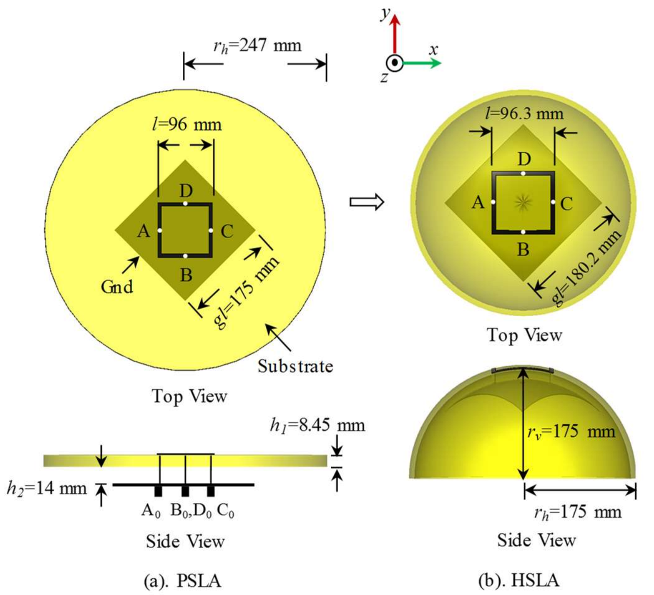



Fig. 3. Top and side views of the SLA; (a) the SLA on a planar substrate and (b) the SLA on a hemispherical substrate.

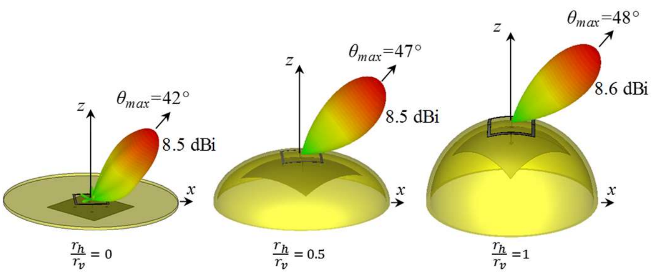



Fig. 4. Effect of substrate bending on the radiation pattern at 2.45 GHz.

Fig. 4 shows the effect of the substrate bending on the antenna radiation patterns at 2.45 GHz when the ratio of $r_h$ to $r_v$ is varied. When only port $A_0$ is excited and the remaining ports ($B_0$, $C_0$ and $D_0$) are open-circuited the antenna provides a linearly polarized tilted beam ($\theta_{max}$) directed away from the excited port $A_0$ (i.e. $\phi_{max}$=0°). It is observed that when $r_h/ r_v$ is varied from 0 to 1 (Fig. 4), beam tilt angle varies from 42° to 48° and that the gain stays nearly constant. It was observed that if the substrate is bent beyond $r_h/ r_v$ >1.3, magnitude of side lobe increases and pattern becomes distorted. The hemispherical configuration ($r_h/ r_v$=1) of the antenna has the highest tilt angle and gain.

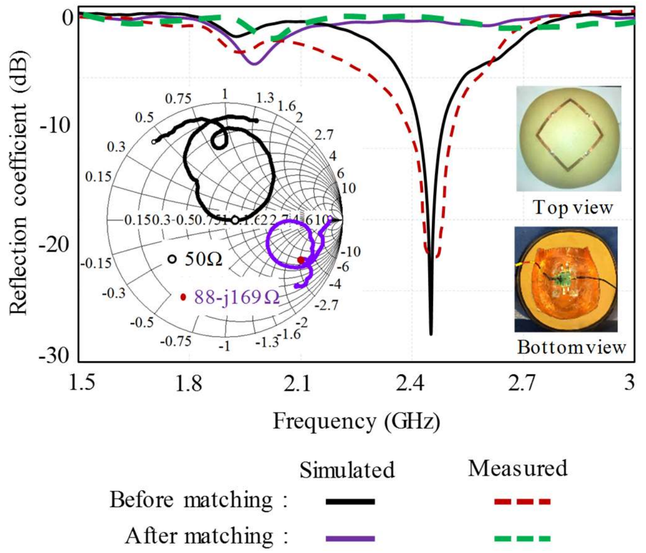



Fig. 5. Reflection coefficient and input impedance of the HSLA; (inset) top and bottom view of fabricated prototype.

Fig. 5 shows the frequency response of the reflection coefficient and input impedance of the HSLA. The antenna shows an input impedance of 88-j169Ω at the 2.45GHz. This causes an impedance mismatch with the standard 50Ω excitation source. Consequently, the antenna exhibits a poor reflection coefficient ($|s_{11}|$ ~ -3dB) at the operating frequency. A two-section stepped coaxial transmission line matching circuits are employed to match the antenna to the switch.

Fig. 6 (a) and (b) show the simulated model and fabricated prototype of two-section stepped transmission line matching network. The matching network on the microstrip has two 9 mm long SMA standard connectors on its either sides. The matching network transforms 88-j169.3Ω from the input of HSLA to 50 Ω. The initial values of characteristic impedance and length of the microstrip line were obtained from [27], and subsequently an optimizer of CST Microwave Studio (CST-MWS) [28] is used for achieving the final values, shown in Fig. 6. The matching network was developed using an FR4 substrate having permittivity of 4.8 and a height of 1.6mm. Fig. 6(c) shows the equivalent circuit of the matching network, which were determined from the network parameter extraction method of CST-MWS. Fig. 5 shows the reflection coefficient and input impedance of the HSLA when integrated with matching networks. With the matching network the HSLA operates efficiently ($|s_{11}|$ < -10 dB) over 2.4 GHz (802.11b/g/n) WiFi frequency band with an impedance bandwidth of 180 MHz (2.36 to 2.54 GHz).

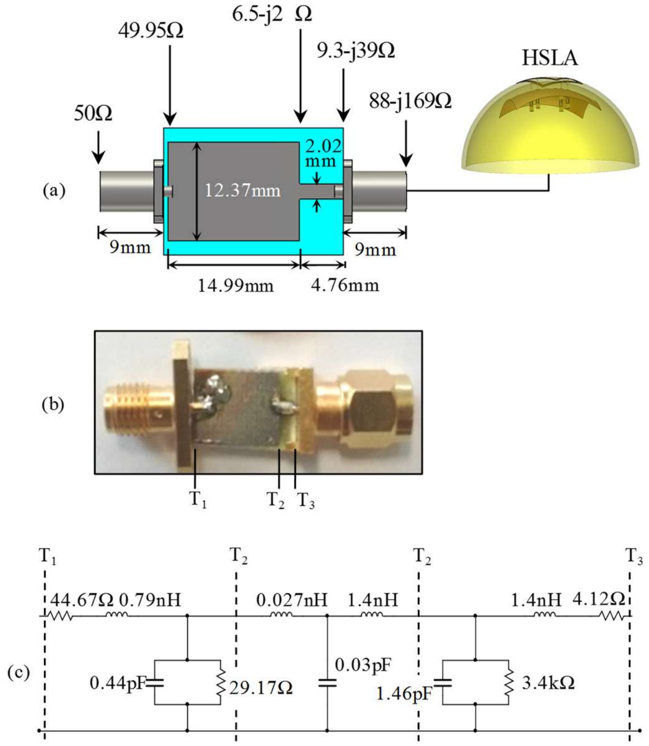



Fig. 6. Matching network: (a). simulated model, (b). Fabricated prototype, (c). Equivalent circuit.

When port $A_0$ is excited and remaining ports ($B_0$, $C_0$ and $D_0$) are open circuited, the HSLA provides a linearly polarized beam, tilted of $\theta_{max}$=48° from the zenith (z-axis). The beam is pointed away from the excited port, i.e. in the direction of $\phi_{max}$=0°. With the matching network the HSLA provides a gain of 9.2 dBi in the direction of maximum radiation with a radiation efficiency of >87% over the impedance bandwidth. The main radiation beam is linearly polarized in the direction of maximum radiation. The magnitude of the cross-polarized ($E_\phi$) component is well below from that of the co-polarized component ($E_\theta$ ), i.e. $|E_\theta| > |E_\phi|$ by over 40 dB. It is shown in Fig. 7 that the SLA maintains its pattern shape over the radiation pattern bandwidth of 250 MHz (2.35 to 2.6 GHz). A variation of 10° (46° to 56°) in beam tilt angle and a variation 0.7 dB (8.5 to 9.2 dBi) in gain is observed over the radiation pattern bandwidth. Outside the pattern bandwidth, the radiation patterns are distorted due to split beam.

Since, the square loop is symmetrical with respect to the centre point of the whole structure, the radiation patterns of other feeding ports ($B_0$, $C_0$ and $D_0$) are similar to that of port $A_0$. Therefore, when any of the four feeding ports are excited one at a time, while remaining ports are open circuited, the HSLA provides a tilted beam of $\theta_{max}$=48° in four different space quadrants of $\phi_{max}$=0°, $\phi_{max}$=90°, $\phi_{max}$=180° and $\phi_{max}$=270°. Thus, by switching the RF input among the feeding ports the HSLA maneuvers its radiation beam over the four quadrants to scan the entire 360° space in front of the antenna. We achieved this beam steering by using an RF switch and an intelligent algorithm for spectrum capacity enhancements. It is described in the next section.

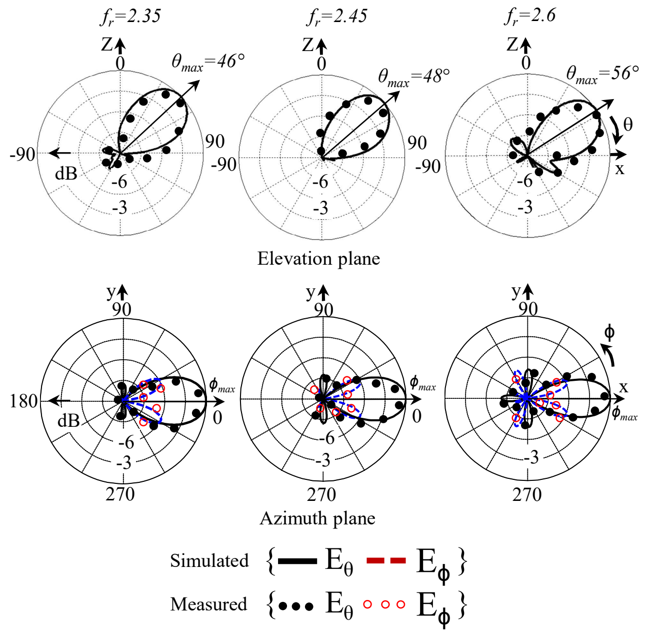



Fig. 7. Radiation patterns of the HSLA over the operating bandwidth.

## IV. THROUGHPUT ANALYSIS

As shown in Fig. 1, the SP4T RF switch is connected to the HSLA using four semi-rigid coaxial cables, each having a length of 110 mm. The main RF In/Out of the switch is connected to the USB WiFi adapter (transceiver) which is interfaced with Raspberry Pi where throughput is measured and examined. The switching control pins of the RF switch are connected to the GPIO pins of the Raspberry Pi that provide the necessary required biasing and switching control voltages. Raspberry Pi runs an intelligent beam-steering algorithm written using C called as the 'Electromagnetic Sense, Analyze and Lock' algorithm. It enables HSLA to lock always to a direction with which the Pi receives the highest RSSI signal value. This algorithm is shown in Fig. 8.

In the laboratory, Fig 2, upon powering of the system the RF switch undertakes a fast sequential switch / scan (in 100 milli sec) of the environment. This provides the four RSSI values for the signal received at the four HSLA ports from the WiFi channel being transmitted from the horn antenna. The horn antenna is set to transmit a vertical polarization ($E_\theta$) WiFi signals at SSID (Service Set Identifier) '5G test' which is synchronized with the WiFi transceiver chip. The Pi compares the four RSSI values and locks the system to the port with highest value. Table 1 shows the four received RSSIs for the four ports and that the system is auto locked to the strongest RSSI port $A_0$ (-65dBm). Thereafter, the system keeps monitoring the link. We set a dynamic setting to ensure that whenever a signal drops below a threshold the system undertakes a fresh scan. For this work, we had a setting that 'if signal drops 3 dB below the current RSSI, in this instance -68dBm' it undertakes a new scan. The threshold to rescan was dynamic and by using a slider on Graphic User Interface on the display it could have been changed easily for any desired value. Both transmitter and HSLA were moved around the laboratory and it was found that in all instances the algorithm always locked to the strongest RSSI signal direction.

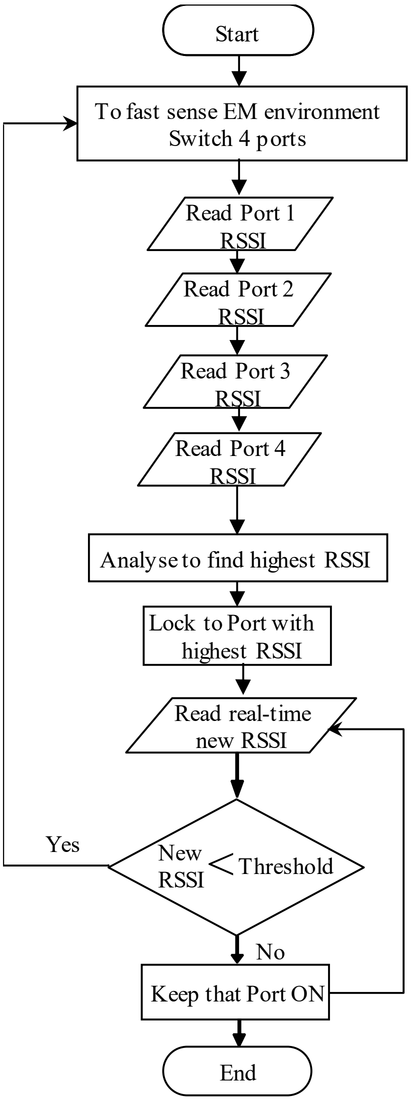



Fig. 8. Flowchart of the Electromagnetic sense, Analyse and Lock algorithm.

We tested system internet throughput on all four ports and found that there was a significant difference between the strongest and weakest signal ports. For instance, the strongest port $A_0$ provided an RSSI of -65 dBm, a downlink of 7.7 Mbps and an upload speed of 6.2 Mbps. This meant that port $A_0$ can fully support full HD duplex video link. In contrast, internet throughput measurements on other weaker ports ($B_0$, $C_0$ and $D_0$) which were operating close to system average noise floor in multipath laboratory setting of -81dBm provided extremely weak data rates. Even down to zero kbps for both upload and download speeds. For instance port $D_0$ RSSI was just 2 dB above noise floor and provided zero data speeds with the commercial WiFi modulation schemes. Therefore, the beam steering enhanced the spectrum efficiency and its capacity for the fixed available WiFi bandwidth. These tests were done on a commercial throughput-measuring site. In addition, the internet horn antenna link was not shared with any other user and was totally dedicated to this experiment. This test quantified the beam steering advantage in a real world of OFDM communications. It showed that a high gain beam steering antenna enabled a device to lock to the direct / strongest signal, and that the device could sustain high definition video in an otherwise weak EM environment. Had the beam steering not present in the same environment, in a worst case scenario the same device would have absolutely zero throughput. This advantage was further evident from the video test that was undertaken. It showed that a full HD was sustained by port $A_0$ with zero packet and frame loss. The other ports offered video conferencing with a weak intermittent service with 90 % packet loss or absolutely no service at all. Thus, for a given weak EM environment beam steering was the difference between a good HD communication versus a very weak or no communication.

Table. I. RSSI, throughput and video qualities of the communication link at four ports of the HSLA.

| | | Port $A_0$ | Port $B_0$ | Port $C_0$ | Port $D_0$ |
|---|---|---|---|---|---|
| RSSI (dBm - average of five repetitions) | | **-65 (locked)** | -75 | -77 | -79 |
| Throughput (Mbps) | Download | **7.7** | 0.9 | 0.3 | 0 |
| | Upload | **6.2** | 0.7 | 0.3 | 0 |
| highest Packet Loss observed (%) | Send | **0** | 90 | 96 | 98.1 |
| | Receive | **0** | 90 | 92.4 | 97 |
| Video Conference link ON/OFF? | | **ON** | Intermittent breaking | OFF | OFF |

As would have been appreciated from the system design that we only used a single antenna for both sensing and communication. Typically, an auxiliary sensing antenna is needed for electromagnetic environment sensing. In this case, we exploited the built in buffers and latency mitigation mechanisms of the TCP / IP WiFi network to ensure that no data is lost in the 100 milli second scan duration. Note, while the switches can operate in nano seconds, a milli seconds scan duration was selected due to relatively slow time response of the USB WiFi adapter. Finally, as demonstrated in this work the algorithm works at the application layer that controls the RF switch and antenna patterns at physical layer. Therefore, in this work the entire middle protocol layers are untouched. Hence, the system can easily be retrofitted to existing non-adaptive communication systems to make them smarter and faster in weak EM environments.

Accepted with corrections: 18th April 2017, IEEE Transactions on antenna and propagation

## V. Conclusion

A pattern adaptive Hemispherical Square Loop Antenna (HSLA) is integrated to Raspberry Pi single board computer. It is demonstrated that in a weak EM environment the adaptive antenna is capable of providing a throughput 7.7 Mbps and can sustain uninterrupted HD video conference. It was demonstrated that in a worst case scenario without having beam steering capability there would have been absolutely no communication (0 bps). The beam steering mechanism is implemented using a smart 'EM Sense, scan, analyze and lock' algorithm running on Pi in C. The algorithm controls the beam direction of the SLA by using an RF SP4T switch linked to the SLA. The proposed system architecture used only a single antenna for both sensing and communications. Finally, the system had the application layer controlling the physical layer for a maximum possible RSSI. Thus, the entire middle protocol layers were untouched.

## References


[1] Cisco, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014–2019" White Paper, 2015.

[2] A. Aloman, A. I. Ispas, P. Ciotirnae, R. Sanchez-Iborra and M. D. Cano, "Performance Evaluation of Video Streaming Using MPEG DASH, RTSP, and RTMP in Mobile Networks," *IFIP Wireless and Mobile Networking Conference (WMNC)*, Munich, 2015, pp. 144-151.

[3] E. Yaacoub, Z. Dawy, and A. Abu-Dayya, "On real-time video streaming over lte networks with mobile-to-mobile cooperation," *International Conference on Telecommunications (ICT), IEEE*, 2012, pp. 1–6.

[4] "MobiTV", [Online]. Available: https://www.mobitv.com/.

[5] R. Anderson, O. Chung, K.M. Davis, P. Davis, C. Prince, V. Razmov, and B. Simon, "Classroom presenter—a classroom interaction system for active and collaborative learning," *Proc. Workshop Impact of Pen-Based Technology on Education (WIPTE)*, 2006.

[6] "Smarthome-Home Automation Systems, Products, Kits, Hubs & Ideas", [Online]. Available: http://www.smarthome.com/.

[7] W. Coomans *et al*., "XG-fast: the 5th generation broadband," *IEEE Commun. Mag.*, vol. 53, no. 12, pp. 83-88, Dec. 2015.

[8] C.-X. Wang et al., "Cellular Architecture and Key Technologies for 5G Wireless Communication Networks," *IEEE Commun. Mag*., vol. 52, no. 2, pp. 122–30, Feb. 2014.

[9] C. E. Shannon, "Communication in the Presence of Noise," *Proc. I.R.E*, vol. 37, no. 1, pp. 10-21, Jan. 1949.

[10] R. R. Choudhury, Xue Yang, R. Ramanathan and N. H. Vaidya, "On designing MAC protocols for wireless networks using directional antennas," *IEEE Trans. Mobile Computing*, vol. 5, no. 5, pp. 477-491, May 2006.

[11] V. Navda , A. P. Subramanian , K. Dhanasekaran , A. Timm-Giel and S. Das, "MobiSteer: using steerable beam directional antenna for vehicular network access," *Proc. 5th international conference on Mobile systems, applications and services*, San Juan, Puerto Rico, Jun. 11-13, 2007.

[12] X. Liu, A. Sheth, M. Kaminsky, K. Papagiannak, S. Seshan, and P. Steenkiste, "DIRC: Increasing indoor wireless capacity using directional antennas," *Proc. ACM SIGCOMM*, Aug. 2009, pp. 171–182.

[13] A. Mehta, D. Mirshekar-Syahkal, and H. Nakano, "Beam adaptive single arm rectangular spiral antenna with switches," *IEE Proc. Microwave, Antennas Propag.*, vol. 153, no. 1, pp. 13–18, 2006.

[14] A. Pal, A. Mehta, D. Mirshekar-Syahkal and P. J. Massey, "Doughnut and tilted beam generation using a single printed star antenna," *IEEE Trans. Antennas Propag.* , vol. 57, no. 10, pp: 3413-3418, Oct. 2009.

[15] A. Mehta and D. Mirshekar-Syahkal, "Pattern steerable square loop antenna," *IEEE Electron. Lett.*, pp. 491–493, Apr. 2007.

[16] A. Pal, A. Mehta, D. Mirshekar-Syahkal, and P. J. Massey, "Short circuited feed terminations on beam steering square loop antennas," *IEEE Electron. Lett.,* vol. 44, no. 24, pp. 1389–1390, Nov. 2008.

[17] P. Deo, A. Mehta, D. Mirshekar-Syahkal, P. J. Massey and H. Nakano, "Thickness reduction and performance enhancement of steerable square loop antenna using hybrid high impedance surface," *IEEE Trans. Antennas Propag.*, vol. 58, no. 5. pp. 1477–1485, May, 2010.

[18] A. Pal, A. Mehta, D. Mirshekar-Syahkal, P. Deo, H. Nakano, "Dual-Band Low-Profile Capacitively Coupled Beam-Steerable Square-Loop Antenna," *IEEE Trans. Antennas Propag.*, vol.62, no.3, pp.1204-1211, Mar. 2014.

[19] [Online].Available:https://www.hittite.com/content/documents/data_sheet/hmc241lp3.pdf.

[20] J. C. Wu, C. C. Chang, T. Y. Chin, S. Y. Huang and S. F Chang, "Sidelobe level reduction in wide-angle scanning array system using pattern-reconfigurable antennas," *Microwave Symposium Digest (MTT), 2010 IEEE MTT-S International*, Anaheim, CA, 2010.

[21] M. P. Daly and J. T. Bernhard, "Beam steering in Pattern Reconfigurable Arrays Using Directional Modulation," *IEEE Trans. Antennas and Propag.,* vol. 58, no. 7, pp. 2259-2265, Jul 2010.

[22] Y. Y. Bai, S. Xiao, M. C. Tang, Z. F. Ding and B. Z. Wang, "Wide-Angle Scanning Phased Array With Pattern Reconfigurable Elements," *IEEE Trans. Antennas and Propag.,* vol. 59, no. 11, pp. 4071-4076, Nov 2011.

[23] A. Pal, A. Mehta, R. Lewis and N. Clow, "Reconfigurable phased array antenna enabling a high gain wide angle beam scanning," *2015 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, Vancouver, BC, 2015.

[24] Various, "Raspberry Pi model B credit card sized minicomputer," Raspberry Pi Foundation, UK, [online] http://www.raspberrypi.org/products/model-b/.

[25] http://www.cisco.com/c/en/us/products/collateral/wireless/aironet-1200-access-point/product_data_sheet09186a00800937a6.html.

[26] "Tenda U1 300Mbps Utral-Fast Wireless USB Adapter-Tenda-All For Better NetWorking," [Online]. Available: http://www.tendacn.com/en/product/U1.html.

[27] S. Rosloniec, "Design of stepped transmission line matching circuits by optimization methods," *IEEE Trans. Microwave Theory and Techniques*, vol. 42, no. 12, pp. 2255-2260, Dec 1994.

[28] CST GmbH. Darmstadt, Germany, [*online*] http://www.cst.com.

[29] Zoom video conferencing and web conferencing service, *https://zoom.us/*