Significant Performance Improvement Obtained In a Wireless Mesh Network Using a BeamSwitching Antenna

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Abstract-The paper describes the performance enhancement obtained by adding an electronically controlled beamswitching antenna to a laboratory test-bed of a wireless mesh network. The in-house designed antenna permits several operation modes offering several beam shapes and directions. This permitted a tenfold throughput improvement, from 0.2 Mbps to 2 Mbps, in a mesh network scenario in the presence of an interferer. The results were obtained experimentally, on an indoor wireless network testbed.

Index Terms—antenna, smart antenna, wireless mesh network, WMN, beamswitching, parasitic array

I. INTRODUCTION

The wireless communications experience significant growth, which can be expected to continue for at least one-two decades due to steadily growing demand for data, due to introduction of new technologies and bandwidth-hungry applications, such as video streaming, IPTV and the Internet of Things. The demand for both higher data rates in the presence of limited frequency spectrum availability and greater degree of every-day convenience has lead to the need for higher spectral efficiency in the communications. There is active research and development of the new methods and technologies enabling this at the physical layer, including multiple antenna techniques, such as multiple input multiple output (MIMO) and smart antennas.

In African context, a significant importance is placed on communication methods and technologies which are cost efficient and well suited to the applications in rural / remote areas. The main criteria usually include affordability, robustness, ability to cover long distances with a minimal number of hops (and so optimized cost of an installation), minimal energy consumption, and high throughput. The affordability includes the cost of the hardware as well as software and licensing. The latter is often a significant cost restricting factor. The robustness usually refers to the ability of a device to operate under harsh environmental conditions and the ability to handle a change in the environment in which the device is operating.

The ability to cover long distances depends on several factors. One is the effective isotropic radiated power (EIRP), composed of the power delivered from the radio frequency (RF) power amplifier to the antenna and antenna's gain. The high gain means that the antenna focuses the radiation in a specific direction rather than spreading it around unnecessarily. This enables to send the signal much further whilst consuming the same amount of power, e.g. when compared to omni-directional antennas.

An antenna [1] with a higher gain offers additional advantage of lower levels of interference it produces, as well as lower level of sensitivity to interference, thus leading to a higher signal to noise and interference ratio (SINR) [2]. Whilst the general RF interference may be low in a typical rural area, the wireless network's self-interference, e.g. when two neighboring network nodes are not synchronized and start to transmit simultaneously, is usually a major bottleneck. An example to this is IEEE 802.11 based networks. Under the scenario of high gain antennas, the focused beams permit to separate the communication channels, even though they may pass through a common medium and use the same frequency, and thus obtain a high throughput.

In MIMO [3], different antennas send different information, including the most trivial case when the information is the same. For example, the IEEE 802.11n uses MIMO technology, and it has a proven track record when applied in urban scenarios with high multipath, thanks to the ability to take advantage of the multipath. This resistance to multipath is often critical in the complex urban or indoor environments, with the multitude of obstacles and large and fast fading. However, the rural environment is usually much simpler - such areas are typically characterized with low density of scatterers. As such, MIMO's ability to take advantage of the multipath becomes limited. As MIMO requires strong real time digital signal processing (DSP) capabilities, it is also a power-hungry approach.

The smart antennas [2], [4] are often associated with MIMO. However, in the context of this paper, the smartness is treated as an ability of the antenna to adapt to the environment, e.g. having some sort of performance based feedback. Under this definition, the smart antennas include adaptive array antennas. Such arrays are able to shape the beam and steer its direction in a way which maximizes the useful signal and minimizes the interference, e.g. by forming a null in the radiation pattern towards the source of the interfering signal. The latter maximizes the SINR. The disadvantage of the traditional arrays, taken from a conventional view, is in the high cost and power consumption. The former is attributed to a high number of expensive RF elements, and the need for high speed circuitry and fast digital signal processors required to perform real-time beam-forming and, sometimes, tracking of the target. The latter is also associated with the need for speed and substantial amount of computational power required to do the processing in real time.

The needs of a rural application are usually different, as the changes are normally not fast but rather quasistatic. If the ability to change the main beam's direction is kept, whilst the speed of reconfiguring a beam is sacrificed, the advantages associated with array antennas may be successfully employed for cost and power restricted fixed rural applications.

This paper considers an application of an electronically switched array antenna to significantly increase the throughput of a wireless mesh network (WMN) without the need to increase the power consumption or cost drastically.

The paper is organized as follows. Section II introduces the array antenna. Section III describes the test environment. This is followed by the demonstration of the results and conclusions.

II. ANTENNA PROTOTYPE

An array antenna is made up by using several individual radiating elements. The principle behind the work of an array antenna is based on the constructive and destructive interference of waves. Considering an example of a transmitting antenna, the elements must be able to emit the electromagnetic waves in such a way that these individual waves have the same phase for the desired direction. This way the total signal, i.e. a superposition of the individual waves, can have the maximum amplitude and thus strength carrying the signal over a maximum distance and making it more resilient to interference. The phases of the waves radiated are aligned by a proper control of the elements.

The ability to cancel the interference incident onto an array antenna is based on using the destructive interference. The signals received by individual array elements are delayed or phase-shifted to ensure that there is a maximum cancellation between the individual signals.

The ability to focus the direction of the beam depends on the number of elements in the array antenna. The more the number of elements, the narrower the beam can be made, or the more flexibility the array can afford in shaping a particular required shape of the radiation/gain pattern.

There is a number of ways to achieve these desired properties of creating a strong beam or forming a null in a specific direction. The traditional arrays normally rely on the phase shifters. This leads to a high count of RF components making them relatively expensive. The digital arrays offer the greatest flexibility, as they permit processing the signal individually, per array element. This however makes them very expensive. In addition, this often leads to substantial power consumption.

This paper focuses on the performance afforded with the parasitic array technology described in detail elsewhere [5]-[17]. In brief, this design includes one active element, which has an RF connection, and four parasitic elements. These elements are terminated into electronically controlled RF switches. By controlling the switches, it is possible to change the phase of the current reflected from the switch, and thus the phase of the current distribution on the element. As the radiation produced by the element, including the phase of the wave emitted is directly defined by the current distribution, this give a means to control the phase-shift of the waves, and thus the shape of the radiation pattern.

The picture of the element is shown in Figure 1. The design is discusses in detail elsewhere [9]-[17].

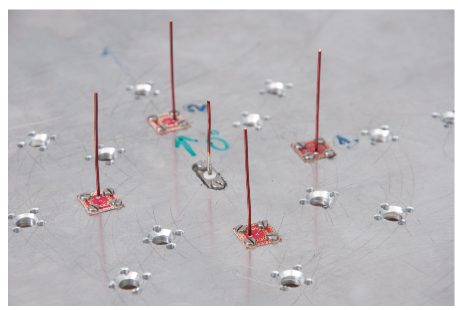


Figure 1. Top view of the antenna's ground plane and four parasitic and one active elements.

The antenna has been modelled and extensively tested in the anechoic chamber of the University of Pretoria, showing a good match between the models and measurements [9]. Figure **2** shows the set up used to measure some of the antenna's performance.

The antenna operates in 2.4-2.5 GHz ISM frequency band, and has several modes. A brief summary is provided in Table 1 (the "code" refers to the value setting a particular mode, through its binary representation applied to switches).

Table 1. Key modes of the antenna and their specifications

Mode(code)	**Half-power beamwidth, deg**	**Worse return loss, dB**
Omnidirectional (15)	360	17
Narrow beam (3,6,9,12)	88	10

In addition, it is worth mentioning that the antenna itself requires less than 1.5 mW of power, making it a very suitable choice for rural and any other energy/power-sensitive applications including wireless sensor networks.

Using only four inexpensive control elements, the antenna permits to build affordable high performance wireless connectivity solutions.

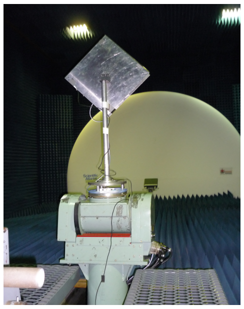


Figure 2**. Set up for measuring elevation pattern of the antenna during the radiation pattern measurements performed at the anechoic chamber of the University of Pretoria.**

III. WIRELESS MESH LAB SET UP

The set up is shown in Figure 3and Figure 4. The former shows that the antenna is connected to the node number 44 located in the centre of the network. The connection is via RS-232 port. In the current setup, the RS-232 port is emulated using a simple program running on another PC and converting the bytes sent to the serial port into the digital signals applied to the RF switches of the antenna. A picture of the setup installed in a 6m by 12m room, is shown in Figure 4. The laboratory test-bed of the CSIR Meraka Institute is configured as a 7 by 7 square grid of small PCs connected into a network in two ways: via 100 Mbps Ethernet (for control purposes) and wirelessly. Each PC is equipped with a wireless network card and a 5 dB omni-directional antenna, shown in Figure 5. The wireless card is based on Atheros chipset, has adjustable output power from 0 to 20 dBm, and sensitivity of -95 dBm at 1 Mbps. The nodes run Linux and use OLSR routing protocol [18], [19].

The antennas are connected to respective wireless adapters via 30 dB attenuators. This effectively limits the maximum communication range at the lowest speed (1 Mbps) down to a maximum of 17 m. Thus introduced restriction on the communication range permits localization of the experiments to the room where the test bed is set up, and also reduces the influence of the external interference.

The propagation in this wireless network has been carefully modeled and found to provide a robust platform for wireless experiments [15], [20].

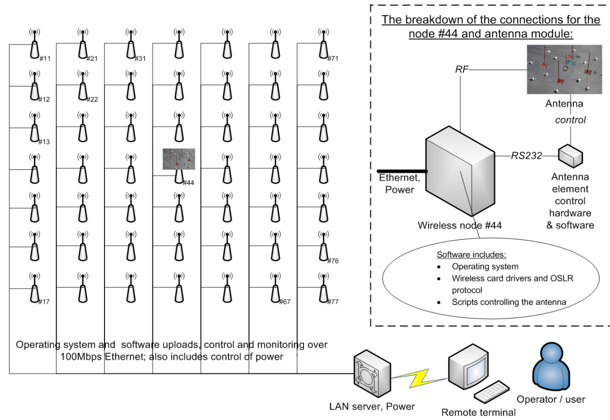


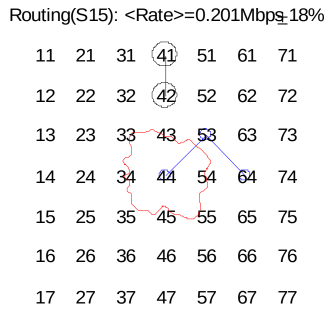
Figure 3. Diagram illustrating the connections between the antenna, the network node, and within the wireless mesh network laboratory.

Figure 4. Picture showing the position of the antenna on the node and an overview of the wireless mesh network laboratory.

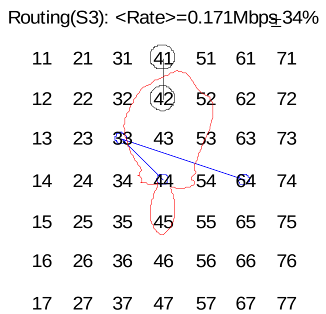
Figure 5. A closer look at an individual node: the RS232 connector is just above and next to the white/green Ethernet cable. The antenna is connected to the wireless card via a 30 dB attenuator.

IV. EXPERIMENT PROCEDURE

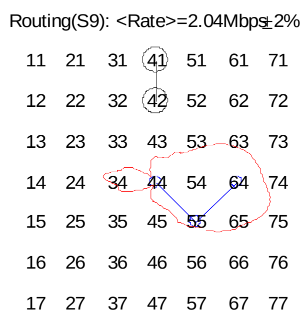
The PC connected to the antenna is able to send the control code to the antenna and thus controls the shape of the radiation pattern between the omnidirectional, and four directional modes. The codes for these main modes are listed in Table 1.



(a)



(b)



(c)

Figure 6. The diagrams showing the links established between the nodes of the wireless mesh network (in blue), the shape of the relative radiation pattern (in red) and the pair of the nodes used to create the interference (in blue). Communication between nodes 44 and 64 use different routing paths (in blue) for different antenna settings (S15=omnidirectional; S11,S13=wide 180deg beam; S3,S9=narrow 90deg beam) and very different performance, in presence of interfering communications due to nodes 41 and 42 (link shown in black). Antenna's radiation pattern (in red) is superimposed on the plots to illustrate the selectivity due to the specific direction and shape of the beams in different modes.

In the experiments, the links were set to operate in IEEE 802.11b mode, locked to 11 Mbps rate, on WiFi channel 14, with 12 dBm power output. As illustrated in Figure 6, the nodes 44 and 64 were forced to communicate traffic to one another, but not directly. The performance of this link was being measured. At the same time, the nodes 41 and 42 were set to communicate with each other, modeling an interferer. The mesh network's routing protocol was permitted to select the most optimum route. Each test was repeated 3 times.

V. Results and Discussions

The results are illustrated with estimates of the achieved throughput using the routes between the nodes 44 and 64 (a blue line shows the route), as shown in Figure 6. The following can be observed:

a) Setting the antenna to an omnidirectional mode (code=15), shown in Figure 6a, resulted in the throughput of 0.2 Mbps ±18% with the route passing through node 53. This low throughput may be explained by the frequent collisions at nodes 44 and 53 due to the nodes 42 and 41, similar to having a low signal to noise ratio (SNR).

b) Setting the antenna to a directional mode, but with the beam directed towards the interferer, resulted in a similar performance of 0.17 Mbps ±34%, with the route passing via the node 33. The throughput is slightly lower and its standard deviation is much higher here, compared to the previous scenario. This may be explained by considering that four times more interference was to be discarded by node 44, compared to the case (a), thus lowering the throughput and creating instability in the link.

c) The radiation pattern was pointed towards the desired user, node 64. Even more importantly, the null of the radiation pattern was pointed towards the interferer, thus reducing the interference incident on node 44 from the nodes 41 and 42. This resulted in the throughput of 2.04 Mbps with low standard deviation of 2%. This shows about 10 times improvement in the throughput, compared to (a) and (b), and can be attributed to the equivalent SNR value much higher (around 14 dB higher, as one can devise from the relative radiation pattern plots in Figure 6) than the equivalent SNR in, for example, a).

VI. Conclusion

The designed prototype of a low power low cost array antenna uses four elements and permits to switch the radiation pattern between several modes, including an omnidirectional mode and four directions for a 90 deg beam. The test in the wireless mesh laboratory has demonstrated the capability of this antenna to improve the throughput in a wireless network by an order of magnitude.

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