High-performance low-power smart antenna for smart world applications

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Abstract—**This paper overviews a low-power beam-switched smart antenna. The antenna operates at 2.4 GHz frequency band, has low power consumption (1.5 mW), and is intended for smart world applications in communications and metering. The antenna has demonstrated 4x improvement in throughput and 2x reduction in latency, as compared to an equivalent gain omnidirectional antenna. The tests were done in a mesh network environment. In addition, the modifications made to the wireless driver permitted the antenna system to perform an automatic failover and link recovery.**

Keywords—antenna, parasitic array, low power, mesh network

I. INTRODUCTION

An antenna system has been developed to address the need for robust and high-performance wireless communications in wireless mesh networks intended for smart world applications.

The wireless mesh networking [1], i.e. self-organizing ad-hoc networks, is used for providing reliable infrastructure for both broadband and machine to machine communications (M2M). An example of the former is the CSIR Broadband4All project [2] which has by now provided Internet access to over 200 rural schools in South Africa alone. The M2M applications also have a large and steadily growing market; for example, ABI research predicts annual home automation device shipments alone to exceed 351 million by 2018.

The wireless networks' performance and the range of applications are often limited by self-interference, range and reliability and cost [3]-[8], [1]. The new applications of technology offering a degree of intelligence and thus-derived advanced functionality, referred to as *smart world*, are often heavily dependent on these factors. For example, the losses of water in water distribution systems may be significantly reduced by introducing real-time or near real-time remote monitoring. At the other end, the components of a complex system, such as containers carried by a trains and ships also require longevity, i.e. low power consumption.

To add to the complications, many of the performance parameters are interlinked. For instance, interference to communications may force retransmission of the data, thus increasing the power consumption. Such interference may originate either from outside of a network or be caused by the very operation of the network.

The self-interference is due to more than one network node transmitting at the same time and thus disrupting each other's waveforms, and usually causes re-transmissions. This normally causes a significant reduction in the throughput (i.e. much slower downloads and uploads), an increase in latency (which is most disruptive for delay-sensitive multimedia communications) and an increased power consumption. The communication range is effectively determined by the ability to achieve a minimum signal strength and signal to noise ratio required by the receiver, i.e. by the transmitter power, antenna gain, receiver sensitivity as well as, again, by the interference. The overall reliability of a network, and thus of the application's smart functionality, heavily depends on the ability of each node to handle failures of other nodes in the network.

Although there are some advanced solutions recently introduced, such as multiple-input multiple-output (MIMO) technology [8]-[11], or just coming up, e.g. Weightless [12], to address the above-mentioned challenges, they have limitations. The MIMO requires digital signal processing and several radio frequency (RF) front-ends, each supporting an individual antenna element. This makes MIMO both power-hungry and expensive. The Weightless ensures up to 30 dB of processing gain and thus-derived robustness by allowing a spreading factor of up to 1000, rendering it slow. A significant degree of the advantages present in both technologies, the speed in MIMO and robustness in Weightless, may be achieved using low-cost and low-power parasitic array antennas [13]-[15].

The smart antenna discussed in this paper is a parasitic array and is able to address many of the above-mentioned challenges. It requires only one RF port and thus offers a low RF component count whilst nearly the same configurability as the more expensive conventional phased arrays. The parasitic elements are used to adjust the phase of the fields to produce the beam of desired shape. A classic example of a parasitic array antenna is the Yagi-Uda antenna [30]. The shape of radiation pattern, i.e. the direction of the antenna's beam may be controlled by varying the loads attached to the parasitic elements.

The work around controlled parasitic array antennas began with [16] and has received significant attention, for example [13]-[26]. Compared to the prior art, this paper introduces

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several advancements. The switched beam design was to increase the speed of operation and to reduce the power consumption and cost. The switched beam configurations may be controlled using a pre-computed look up table, enabling a high speed switching. The power consumption and cost are reduced, as compared to ESPAR (electronically steerable parasitic array radiator) designs needing additional circuitry to work with varactors and extra processor cycles to run searches, e.g. [20]. The power consumption is also lower due to the choice of complementary metal–oxide semiconductor (CMOS)-based control elements [14] requiring orders of magnitude less power compared to the designs based on PIN diode switches, e.g. [19]. The size has been significantly reduced as compared to our previous design discussed in [14] and [15], although it remains comparable to other published designs. Last but not the least, the control of the antenna is done in across several layer of a network stack, via a modified WiFi driver, permitting a node to switch the beam from one link to another, should a link fail. This functionality is an alternative to various access control schemes published elsewhere, e.g. [27]-[29], providing compatibility with existing protocols.

The paper is organized as follows. Section II describes the antenna system, at component level, from an overview of the design to the individual performance. The next section focusses the testing done in a mesh network environment and the network level performance. The paper is concluded with the summary in Section IV.

II. ANTENNA SYSTEM DESCRIPTION

The antenna introduced in this paper is an advanced and compact array antenna-based system which sends/receives the signals into/from the air, with the direction of transmission/reception being controlled from the operating system (OS) level driver.

The antenna system is composed of the parasitic array antenna, driver software code, and an embedded controller. The system diagram is shown in Fig. 1a. The driver working under Linux, sets the beam in accordance to the node to be communicated with. To set the appropriate beam shape, the driver sends the corresponding beam shape code to the RS232 port. The embedded controller receives the codes from the RS232 port and sets the appropriate voltages for the array antenna elements to configure the respective beam shape. To improve the usability and convenience, the low power controller draws the power from the RS232 port lines [34]. The next subsections describe the system components in some more details:

A. Antenna

The antenna was designed to provide robust high performance communications in a wireless mesh network operating at 2.4 GHz frequency in the industrial scientific medical (ISM) license-exempt band and based on our previous work, mainly [4], [14], [15], [22] and [34].

The ability of the array to focus the electromagnetic radiation helps to combat the external and self- interferences. A summary of the achieved radio frequency (RF) and antenna characteristics is shown in *TABLE 1* and the overall benefits listed in Section D to follow.

The antenna modeling and design were accomplished using the modelling tools [31] and [32] and followed the approaches devised and the radio frequency (RF) switch and printed circuit board (PCB) data measured earlier, in [4], [14], [20], [23], [25] and [26]. An iterative optimization was used for the design, taking into account several criteria for an acceptable return loss, maximizing the gain and controlling the shape of radiation pattern. The optimization variables were the height of the antenna's active and parasitic elements and the radius at which the parasitic elements are away from the active element.

The manufactured prototype is shown in Fig. 1b. It is compact, under 10 cm in any dimension, and light-weight (under 200g). The active and four parasitic elements are mounted on the metallic groundplane with a sleeve. The sleeve helps to lower the beam and improve gain, as discussed in [20]. The active element is connected to an SMA connector. The parasitic elements are mounted on the PCBs with RF switches on one side and wires playing the role of parasitic elements on the other side.

The heights of the active and parasitic elements were set to 28.2 mm and 37.8 mm, respectively. The distance from the active to parasitic elements was 34.2 mm. The radius of the ground plane was 94.4 mm. The height of the sleeve was 22 mm.

The antenna is matched to a standard 50 Ohm coaxial line with an SMA connector. Also, it consumes very little power (the antenna consumes under 1.5mW). The low power consumption is due to the use of the CMOS RF single-pole dual-throw (SPDT) switches [14].

The antenna is designed to form several predefined different beam shapes (radiation patterns): from omni-directional to directional beams. With four equidistantly spaced parasitic elements, each shape may be set for one of four predefined directions. In this design, the directions were spaced equidistantly, at 90 deg from one another. This permitted various modes of communication. For example, an omnidirectional mode of operation is equivalent to a typical

TABLE 1. MAIN CHARACTERISTICS OF THE ANTENNA (AT 2.45 GHZ FOR THE ESTIMATED RADIATION PARAMETERS; FOR THE BAND 2.4-2.5 GHZ FOR THE MEASURED IMPEDANCE PARAMETERS). HPBW STANDS FOR *HALF POWER BEAM-WIDTH*, RL STANDS FOR *RETURN LOSS*.

Mode (code value)	**Max gain*, dBi**	**HPWB*, deg**	**Maximum gain span*, dB**	**Worst RL, dB**	**Impedance 10-dB bandwidth, MHz**
Omnidirectional (195)	0.1	360	0.4	-20.4	> 500 MHz
Wide beam (67)	3.3	170	n/a	-16.3	> 450 MHz
Narrow beam (3)	5.1	106	n/a	-12.4	>350 MHz

antenna used in WiFi devices, whilst a directional mode is closer to a dish, panel or horn antenna.

The antenna advances from an earlier beam-switching design [14], [15], whilst deriving from there the design for the low-cost and low-power electronically controllable parasitic elements. A different geometrical configuration permitted to achieve a wider impedance bandwidth, as compared to the previous design. The usage of a designed compact groundplane with a sleeve permitted. This makes the antenna more tolerant to inaccuracies in manufacturing.

B. *Modified WiFi driver*

The modifications were applied to an original MadWiFi (Multiband Atheros Driver for WiFi) Linux driver for 802.11a/b/g universal network interface card (NIC) for Atheros chipsets cards.

The MadWiFi is the bridge between end user applications and the NIC. Just like most of the IEEE802.11 drivers, the original MadWiFi was developed with the assumption of using omnidirectional antennas, even though more than one antenna can be supported for diversity purposes depending on the number of antennas handled by the hardware.

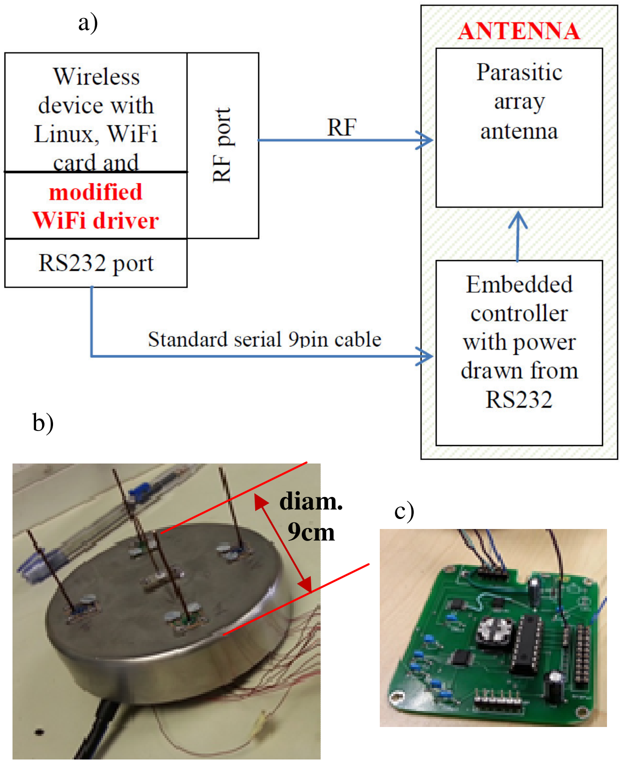

Fig. 1: a) Block diagram of the antenna and its typical connection to a wireless node. b) Antenna with one active and four parasitic elements, and an auxiliary board for manually configuring the antenna. c) The embedded controller drawing power from RS232, being tested. The pictures in b) and c) are shown in proportion.

The modification of the WiFi driver included introduction of the data structures and control mechanisms making the driver aware of the additional capabilities afforded by a beam switching antenna [33]. This enabled the driver to switch to an alternative route or beam when a routing metric for a current route becomes unusable.

The overall network level performance of the antenna acting as a smart antenna, i.e. when controlled by a modified wireless driver, is discussed later, in the Section III.

C. *Embedded antenna controller deriving power from RS232*

The controller was made to perform two functions:

- The controller derives the power from RS232 lines, and converts voltages to the levels suitable for powering and controlling the CMOS RF switches used to electronically control the parasitic elements.
- The controller receives the control codes from the host computer, as sent by the driver, and sets the RF switches to the appropriate states. Samples of the codes (decimal equivalent of the binary number that is send to the RS232 port) are shown in the brackets in the first column of *Table 1*.

The controller permitted to connect the antenna to various platforms without any software or hardware alterations. The manufactured prototype is shown in Fig. 1c. Additional details about the design and features of the controller may be found in [34].

D. *Benefits*

The overall benefits of the design, as compared to an omnidirectional antenna or a fixed directional antenna, are due to a combination of the physics of array antenna's operation, an advanced routing protocol, and compactness of the mechanical design. The following are the basis for expected improvements:

- The array antenna takes advantage of constructive interference and thus permits to focus the radio frequency (RF) energy in the desired direction. This reduces the RF interference to other nodes, and, for the same reasons and by reciprocity, makes a wireless link with such antenna equally less sensitive to the general interference. At the same time, focusing the energy instead of spreading it all around, permits a longer communication range, as compared to a single antenna element of the same size.
- Accepting less interference by the antenna (as described in the previous point) enables having a higher signal to noise and interference ratio (SINR) at the receiver and thus improves speed and robustness of, and lowers delays in communications.
- In addition to the above-mentioned physical layer benefits, a superior level of robustness in a wireless mesh network is achieved by realizing the failover intelligence, i.e. the ability to switch to an alternative route in case of a failure of another node in a link. The failover is implemented by modifying the MadWiFi

wireless driver to enable support for the switched beam antenna functionality.

III. NETWORK LEVEL PERFORMANCE

The system has been tested in a laboratory environment, as indicated with Fig. 2. It was in a 6.7 m × 6 m test room. In Fig. 2, the numbers 1-3 denote the respective wireless router nodes. The notation *SA* refers to *the smart antenna-equipped node*. In the figure, the location of the nodes is in exact proportion with the actual set up.

For all of the tests, the antenna was compared against an omnidirectional antenna of equivalent maximum gain. In practice, this meant that each set of experiments was done twice: i) with the smart antenna and ii) with an ordinary omnidirectional antenna of the gain value approximately equal to that of the smart antenna. Several network level parameters were tested:

- Network latency was estimated using Linux command *ping* sending packets from one to another node and measuring the time for the ping packet to return, with configurations including one and two hops;
- Network throughput was estimated using Linux command *iperf* (which sent a burst of traffic from one node to another and measured the total number of bytes sent over the defined period of time, thus deriving the throughput in MB/s).
- Received signal strength indicator (RSSI) values were recorded for the different configurations.

Each test was repeated 5 to 10 times to ensure repeatability of results.

The tests show that the system achieved up to 3.9× throughput speedup, and up to 2× reduction in the latency, over a traditional monopole antenna with equal gain.

The operation of the failover feature for a failure of a node in a mesh network was tested by breaking up the communication to the middle node. In a two hop scenario, there are two alternative routes available to communicate (such as the routes SA → 2 → 3 and SA → 1 → 3 in Fig. 2). The power of the middle node (2) was switched off. This forced the routing to switch to an alternative route. The time to switch to an alternative route was measured by continuously running ping and identifying the time required to re-establish a connection to the final destination (node 3), from the moment of losing the connection.

The tests showed the successful switch to a live node within 8 seconds. This delay in the establishing the alternative route is dependent not only on the antenna system under test, but also on the lower communication stack (Network, Link and Physical layers) as the routing was based on the Optimized Link State Routing Protocol (OLSR).

It was also be noted that the recorded RSSI values for a standard omnidirectional and our smart antenna indicate that the signal strength when using our antenna is about 4-7 dB higher than that for the omnidirectional antenna. Although this quantity is likely to be affected by the signal to noise ratio and re-reflections in the test environment, the value may be interpreted to indicate the possible communication range improvement due to the smart antenna, by up to about 2 times.

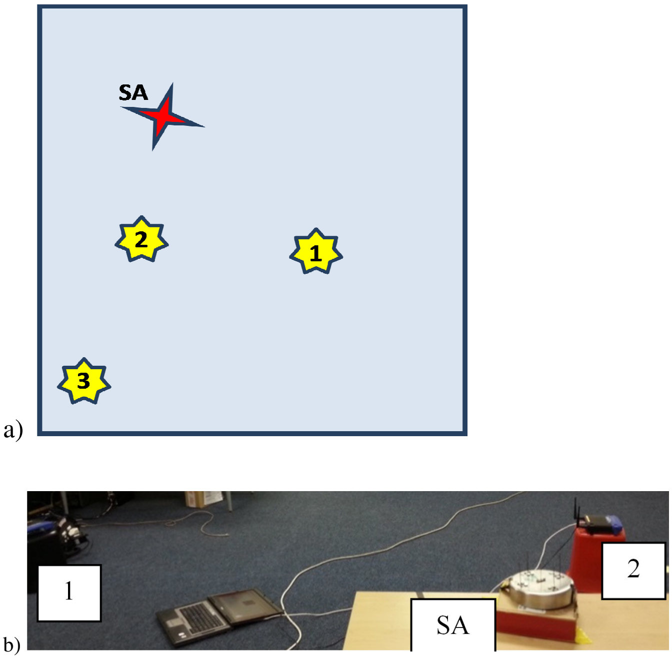

Fig. 2: Test configuration: a) layout overview and b) the picture. For practical considerations, the nodes were raised using the inverted plastic bins. The node 3 was set up with no antennas and under the bin, in order to ensure it cannot communicate with the smart antenna (SA) node directly.

IV. SUMMARY

A robust smart antenna system comprising of a switched beam parasitic array antenna, an antenna controller and operating system level modified wireless driver, has been designed, prototyped and tested, from RF level to the network level performances in a mesh network.

The results show that, in a mesh network, the resultant system significantly outperforms an omnidirectional antenna of the same gain. The throughput was found to be four times higher and the latency two times lower, as compared to the omnidirectional antenna. The intelligence built into the driver controlling the smart antenna also permits to recover a mesh node from a link failure, with recovery taking less than 8 seconds. This high performance was achieved despite very low power consumption by the antenna of less than 1.5 mW.

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