A Smart and Low-cost Enhanced Antenna System for Industrial Wireless Broadband Communication

Moh Chuan Tan[1, 2, a)], Minghui Li[1], Qammer H Abbasi[1], Muhammad Imran[1]

[1] School of Engineering, University of Glasgow, Glasgow G12 8QQ, United Kingdom
[2] Research and Development Department, RFNet Technologies Pte Ltd, Singapore 319319
[a)] Corresponding author: tmohchuan@rfnetech.com

***Abstract*—The aim of this paper is to investigate the traditional wireless local area network (LAN) deployment methods, challenges, and proposal of a novel smart antenna technique to mitigate the problems. In this paper, the focus is on the wireless link between cars to the road-side base station or trains to the trackside base station with fixed access point serving multiple mobile clients. A low-cost, highly scalable, long-range, half duplex hybrid smart antenna architecture with capability of direction of arrival (DOA) estimation and adaptive beamforming integration is proposed. The deployment cell size simulation result shows a drastic reduction in the number of equipment needed to cover the same service area as compared to the traditional method. The results will be of great importance for the future wireless deployment in the transportation market, knowing that the installation cost and maintenance cost are a major cost factor.**

***Index Terms*—smart antenna system, beamforming, broadband.**

I. INTRODUCTION

Global security concern and public safety have drawn tremendous interest from the industries to provide a reliable and high-capacity infrastructure to support security-related applications. Transferring high bandwidth closed-circuit television (CCTV) footage over the air to the operation and command center becomes possible with the latest wireless technologies such as LTE, 5G, and 802.11ac multiple-input and multiple-output (MIMO) technology. Various wireless infrastructures were set up recently to support the increasing demand for the wireless data pipe, this created a common issue such as congestion in the wireless space. Even though the spectrum is well regulated and controlled by local authorities, however the congestion of the license-free spectrum such as 2.4 GHz and 5 GHz industrial, scientific, and medical (ISM) band remains a big concern to the local system integrators. It's essential to have a smart infrastructure that can adapt itself to the highly congested environment.

Transportation and automotive sector have gained benefits from the advancement of wireless technology. To provide a reliable and high-quality service to the industries, the wireless system must be able to co-exist with other wireless systems in the same vicinity, regardless of its application and technologies. In most of the real-life wireless local area network (LAN) deployment, especially in transportation environment, the base station is required to communicate with multiple mobile or stationary clients within the service area. Fig. 1 shows the traditional method to set up the base station at roadside or tunnel to serve the moving vehicles or trains, where the omni-directional antenna is used for 360° coverage. Yellow cells represent the access points coverage and orange cell represents the coverage for mobile clients.

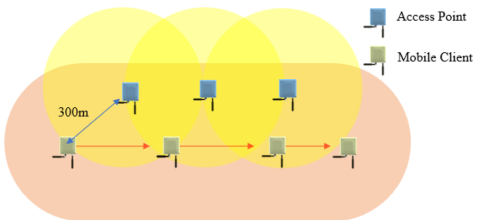

Fig. 1. Conventional point to multipoint deployment

For traditional access point deployment, the access point transmitting at 17 dBm power with 10 dBi antenna gain, the calculated cell size is approximately 300 m. The potential issues with the existing deployment are:

i. Small cell radius due to lower antenna gain, and thus more access points are needed. For example, a 10 km road requires 34 access points.
ii. Mutual interference between adjacent cells if they are operating on the same frequency.
iii. High deployment cost to lay cables, securing poles, power etc.
iv. High maintenance cost as the number of access point increases.

The smart antenna comes in as a right candidate aimed to harmonize the congested wireless environment. There are various methods available to realize the smart antenna function such as analog beamforming [2-6], digital beamforming [8] and hybrid beamforming [7], and each of the methods has advantages and disadvantages. For example, analog beamforming has its cost advantages, however it lags flexibility to perform precise direction of arrival (DOA) and adaptive beamforming, in addition, it usually comes with big size. Digital beamforming involves software & hardware realization to form the beam digitally using field programmable gate arrays (FPGA), but each antenna has its own radio frequency (RF) subsystem that makes the system extremely costly. The advantages of the digital beamforming system are its flexibility to perform beamforming analysis and implementation such as DOA and adaptive beamforming via high-speed FPGA. Hybrid beamforming combines both analog and digital beamforming components that are able to perform beamforming digitally and maintain the cost low.

In this paper, we propose a low-cost enhanced hybrid beamforming system with half-duplex capability, narrow beamwidth and improved communication range that is suitable in the transportation market.

II. PROPOSED HYBRID BEAMFORMING TECHNIQUE

To overcome the current limitations, in this paper a smart antenna system is proposed, which allows the base station to steer the beam towards the mobile client and null off the interference by making use of beamforming technique. Adaptive beamforming can be incorporated to dynamically steer the beam on-the-fly by tracking the client direction using the direction of arrival technique.

Hybrid beamforming antenna system was chosen as it combines the best of both analog beamforming and digital beamforming in a hybrid structure. The hybrid beamforming architecture consists of a low-dimensional digital beam former followed by an RF beamformer implemented using analog phase shifters, targeted to achieve low deployment cost and high scalability. The cost is further reduced by utilizing a patch antenna array built from low-cost dielectric materials. To combat the adjacent cells interference and to improve air space efficiency, the traditional omni directional antenna will be replaced with beam-steerable, narrow beam width, high-gain, directional antenna. With this technique, when the clients are roaming within the service area, both the radiating beam of the access point and mobile client will steer and adjust to each other. Fig. 2 exhibits the radiation beam of the access points and client dynamically steer to follow the direction of the access points and clients. The calculated communication distance is listed in Table I.

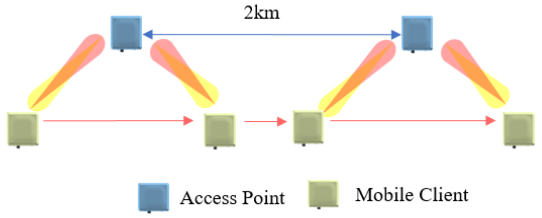

Fig. 2. Proposed deployment using smart antenna for the transportation systems

The benefits gained from the smart antenna are:

i. Longer coverage distance due to the higher gain antenna, and thus less access points are needed. For example, a 10km road requires 5 access points.
ii. Adjacent cell interference reduces due to narrow beam width
iii. Low deployment and maintenance cost.
iv. Energy saving in equipment usage.

TABLE I. ACCESS POINT DEPLOYMENT WITH SMART ANTENNA

TX Power dbm	*Ant Gain dBi*	*Distance Km*	*Calculated RSSI dBm*	*Practical RSSI dBm*	*Min. RSSI dBm*
17	18	2	-60.3	-70.3	-70

For access point deployment with a smart antenna, the access point transmitting at 17 dBm power with 18 dBi antenna gain, the calculated cell size is approximately 2 km, compared to traditional deployment distance of 300 m as mentioned before. The smart antenna system significantly increases the communication range and restricts the radiation beam to desired directions; hence, the air usage efficiency is improved significantly.

Previous work done on hybrid beamforming [9], concluded that if the number of RF chains is twice the total number of data streams, the hybrid beamforming structure can realize digital beamformer exactly, regardless of the number of antenna elements. The similar works [9-10] on the hybrid beamforming architecture from literature could perform simple beamforming task, however for practical long-range deployment, half-duplex communication, receiver sensitivity and transmit power shall be considered as well.

In this work, a compact half-duplex hybrid beamforming system is proposed, the RF front-end sub-module consists of a single frequency up-converter for the transmitter and a single frequency down converter for the receiver that serves multiple antennas and achieves half-duplex communication needs, in addition, the power amplifier (PA) and low noise amplifiers (LNA) are added to increase the communication range. The proposed structure could reduce the cost by multiplexing a single up/down converter to serve N numbers of antennas in a single sub-module shown in Fig. 3.

Each of the sub-module is designed to perform 90° beam steering, thus to cover 360°, the smart antenna system needs 4 of the sub-modules, referring to Fig. 3. The beamforming processing for M sub-modules can be performed by a single FPGA.

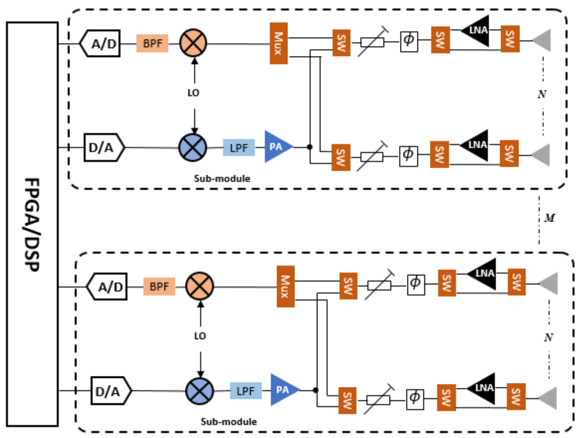

Fig. 3. Proposed functional block diagram for the low-cost half-duplex hybrid beamforming system

Fig. 3 exhibits the basic functional block diagram of the proposed hybrid beamforming. The operation of the proposed hybrid beamforming antenna system can be explained as follows. During receiving, the RF signal travels from the transmitter arrivinged at the *N* antennas with different phases depending on the direction of the transmitter, the received signal will then be further amplified by the LNA and going through the phase shifter and attenuator, the phase shifter and the attenuator can be selectively enabled or disabled depending on the software needs. The received signal is then multiplexed and sent to the downconverter to convert the gigahertz (GHz) frequency to megahertz (MHz), which can be possibly processed by the analog to digital converter. The baseband signal is then fed into the FPGA for digital processing such as DOA estimation and adaptive beamforming weight analysis.

For transmission, the baseband signal from FPGA passing through the digital to analog converter to perform the digital to analog conversion; the modulated signal is input to the mixer to convert the intermediate frequency to high frequency; and the high frequency is amplified by the PA and split into *N* paths before it's transmitted. The phase shifter and attenuator at each transmit chain is programmed with predefined beamforming weight. The beam is formed when the RF signal radiated from the *N* antennas with different beamforming weight.

III. Antenna Design and Simulation

To have an antenna that can mitigate the problems highlighted in the earlier section, below are some key antenna requirements to be considered during the design stage.

a. High gain and small beam width
b. 360° beam steering capability
c. Null for interference
d. Low-cost

The proposed beamforming system with the small beamwidth high-gain antenna can improve the cell coverage size along the road or tunnel, thus reducing the access points needed (Table II).

TABLE II. Calculated Cell Size

Deployment method	***Cell Size Km***	***Estimated number of AP per 10km***
Traditional Method	0.3	34
Proposed Smart Antenna Method	2	5

In this work, one of the targets is to achieve a low-cost and commercially affordable smart antenna, therefore another area of research is concentrated on the printed circuit board (PCB) patch antenna. In the practical automotive environment, the automotive vehicle such as car, bus or train is subjected to severe vibration, and the rigid PCB antenna can provide the good mechanical strength which is important for the automotive environment.

Microwave CST software is used to design and simulate the antenna. At this moment, a single element rectangular patch antenna was designed and simulated, the subsequent task involves designing of microstrip feed networks to integrate the single antenna into an antenna array with higher gain and narrower beam width targeted for beam steering function. A prototype will be fabricated for measurement.

The preliminary antenna design involved calculating and simulating the single rectangular patch antenna with CST tools. For 5.5 GHz operation, the antenna parameters are calculated in Table III using a low-cost FR-4 substrate with dielectric constant $\varepsilon_r = 4.3$.

TABLE III. Antenna Parameters

Parameter	W_g	L_g	W	L	L_f
Value	26.35	22.18	16.75	12.58	8.8
Parameter	W_f	x_o	y_o	t_p	h_s
Value	2.93	2	4	0.2	1.6

The simulated antenna operating frequency is 5.536GHz with a gain of 1.85 dBi, the simulated result agrees well with the calculated result. The simulated reflection coefficient of -22.5 dB, it can be further optimized by adjusting the inset-fed notch width x_o. The simulated HPBW is around 95°, to achieve narrower HPBW, and higher gain, future work involves integrating the patch to form an antenna array, followed by matching and optimizing the microstrip feed.

IV. Conclusion and Future Works

In this paper, the current deployment issues and the proposed smart antenna system to mitigate these issues in future transport systems have been identified. Better airspace efficiency, lower deployment cost, less energy consumption and interference performance improvement are expected to gain from this work. A half-duplex hybrid beamforming technique has been proposed as a suitable candidate for the transport applications. The half-duplex structure enables the transceiver function within a single module instead of separate transmitter and receiver module. The flexible RF frontend is built from modular block consists of LNA, phase shifter, PA, analog to digital converter (ADC), and digital to analog converter (DAC) are highly scalable for future expansion. Finally, it has been proposed that the low implementation cost can be achieved by the hybrid structure and low-cost antenna materials. The smart antenna deployment cost is expected to be 3 times lower than the conventional deployment. The future works include designing an antenna array resistant to vibrations and prototype to support beamforming, followed by, developing the hybrid RF frontend to digitize the RF wave for digital processing and beamforming implementation. A massive field trial will be carried out to validate the smart antenna performance.

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