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Design and Implementation of a High-Gain Compound Yagi Antenna

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ABSTRACT

This paper presents the design and implementation of a high-gain compound Yagi antenna using aluminium rail of thickness, 2mm with high electrical conductivity and reflecting ability. The antenna operates in very high frequency (VHF) and ultra high frequency (UHF) bands covering a frequency range of 174 to 790MHz. It has a gain of 16.7dB and a radius of coverage of about 290km. It was constructed as a prototype antenna and tested at Hanala Motel and Kogi State University (KSU) staff quarters where signals from NTA 12 (Lokoja), NTA 8(Enugu), NTA 23 (Anpka), NTA 10 (Makurdi), OSRC 27 (Akure), CTV 55, (Lokoja), and NTA 6 (Anyigba) were received with sharp picture and audible sound. Better receptions were recorded for NTA 10, CTV55 and OSRC27 on extremely clear, calm and cool days.

Key Words: Design, Implementation, High-gain, Compound, Antenna.

INTRODUCTION

Communication is defined as the sharing of experience [4]. It enables humans to share experiences indirectly or vicariously fostering interpersonal bond and strengthening the economy, culture and traditions of a society. Through communication, economists, scientists, technocrats, technologists and researchers can share ideas, and deliberate on new findings so as to chart the way forward. The social and economic need for direct forms of communication has led to the evolution of various forms of communication.

In the past, people used crude methods such as smoke signals and drum beats for transmitting messages. These methods were slow, painstaking, ineffective and are no longer in vogue because of better discoveries and inventions. One of such inventions was the discovery of electromagnetic waves and antennas. The existence of electromagnetic waves was predicted by James Clerk Maxwell in 1865, confirmed by Heinrich Hertz in 1885 and used by Guglielmo Marconi in 1901 about the same time that the Hertzian antenna was invented to develop a radiotelegraph system. The discovery of electromagnetic waves totally and permanently changed man's system of communication for good.

Electromagnetic waves are the result of the interaction between changing electric and magnetic fields which are perpendicular to each other [9]. They are invisible and travel at the speed of light with enormous ability to carry information from one place to another in a split-second. These waves are used in medicine, radio communication, radar system, satellite system etc. Of all electromagnetic waves, radio waves have the fastest growing applications.

Radio waves are generated by electronic devices such as transmitter and propagated through transmission lines or atmosphere. The propagation of information-bearing radio-waves is greatly aided by antennas which in this case enhance the transmission and reception quality.

Antenna is a transducer designed to transmit or receive radio waves by converting radio-frequency electrical currents into electromagnetic waves and vice versa. They exist in various shapes and sizes, namely; log-periodic, rhombic, ferrite, Yagi antenna, etc. This paper discusses the design and implementation of a high-gain, compound Yagi antenna to operate in the VHF and UHF bands. . A number of modifications meant to increase directive gain and produce a better performance are made to the well-known Yagi antenna herein. It is hoped that this antenna, when well-positioned, will give clear picture and sound to users in offices, hostels, banks, hotels and homes.

2.0 COMMUNICATION THEORY

Radio waves are a major component of the electromagnetic spectrum used for information transmission in radio, telephone, satellite, radar, TV communication systems etc. [3].

Classically, they are thought of as smooth, continuous fields propagated in a wave-like manner, and characterized by frequency (f), wavelength (λ) and speed (c) which are represented by the equation:

$$C = \lambda f \qquad (1.0)$$

where C, the speed of light = $3x10^{8}ms^{-1}$. Equation 1.0 plays a useful role in the determination of the lengths of Yagi antenna elements. As a wave, the radio wave undergoes reflection, refraction, interference, polarization etc.

Quantum mechanically, the radio wave is believed to consist of photons (particles) whose electromagnetic energy, E is :

$$E = hf \qquad (2.0)$$

where h = Plank's constant = $6.626x10^{-34}$Js. This particle nature of radio-waves is characterized by absorption, reflection and heat. Depending on the situation, this energy could be immediately re-radiated and appear as scattered, reflected or transmitted radiation [12].

Radio waves are categorized into bands of frequencies called radio-wave bands. These bands form the transmission bandwidth in communication, carrying transmitted information from one place to another [10]. Table 1 shows the radio-wave bands according to international designations.

Table 1.0: Radio Wave Bands

Designation	**frequency Range**
Extremely Low Frequency (ELF)	3-30Hz
Very Low Frequency (VLF)	3-30KHz
Low Frequency (LF)	30-300KHz
Medium Frequency (MF)	300-3000KHz
High Frequency (HF)	3-30MHz
Very High Frequency (VHF)	30-300MHz
Ultra high Frequency (UHF)	300-3000MHz
Super High Frequency (SHF)	3-30GHz
Extremely High Frequency (EHF)	30-300GHz

For communication purposes, the usable frequency spectrum extends from about 3Hz, through 300GHz, to about 100THz, where research on laser communication is taking place [11]. This spectrum is shared by civil, government and military users of all nations according to International Telecommunications Union (IIU) which spells radio relations.

The VHF and UHF radio waves are propagated principally by line-of -sight; others are tropospheric, ionospheric transmission and satellite communication. They are also used for FM and TV broadcasting. Their propagation is enhanced by using microwave links and satellites. These bands are vulnerable to high losses when transmitted through the troposphere, so the transmitter requires a lot of power. Consequently, line-of-sight transmission using antennas is the best for VHF and UHF.

The process of transmission begins with the production of a non-electrical signal by the transducer, which is amplified and used to modulate a carrier wave generated by an oscillator in the transmitter. The carrier wave acts as a carrier of information bearing signals. The information is encoded by a process called modulation which refers to the variation in the amplitude, frequency or phase of the carrier wave. The modulated carrier is amplified and then applied to the transmitting antenna that converts the electrical signal into electromagnetic energy for radiation into space through communication channel at the speed of light and transmitted not only by line-of sight, but also by deflection from the ionosphere. In space, the receiving antenna intercepts the radiation, and feeds it to a receiver which reconverts it back to sound and/or visual signal [6].

3.0 ANTENNA

An antenna is a system of elevated conductors which couples the transmitter and receiver to space [7], passing radio-waves from the transmitter to the receiver. Antennas are usually made from conducting materials like copper and aluminium, with the efficiency depending on size orientation, transmitter output, antenna parameters such as radiation pattern and impedance matching, and weather conditions [1]. They transmit or receive video and audio TV signals in space and geological exploration, marine, satellite and radar communication.

An antenna, irrespective of the type, may function as a transmitting or receiving antenna. Antenna characteristics are essentially the same regardless of whether it is transmitting or receiving electromagnetic energy. Transmitting antenna has the least critical impedance, being the source of energy with receiving antenna having the most because it is the point where power is consumed. In a situation where a resonant receiving antenna is used, the impedance becomes fairly exact in both cases. The energy is transmitted by space wave, so the transmitting antenna must be very tall to increase the line-of-sight distance.

Television receiving antenna works by intercepting electromagnetic wave and absorbing energy from it. The electromagnetic energy induces in it alternating currents which are transferred to the receiver for detection and conversion into audio-visual waves. For maximum signal to be received, the antenna reactances must match that of the cable transmission line that goes to the receiver, thereby cancelling out the reactances [1].

An antenna may be resonant or non-resonant. A resonant antenna is that in which current distribution exists as a standing wave pattern. They radiate electromagnetic energy equally in all directions and are said to be omnidirectional. Examples are loop, ferrite rod antenna etc [9].

A non- resonant antenna is that in which current exists as a traveling wave. It radiates electromagnetic energy in a unidirectional manner. Examples are Yagi, long-wire, rhombic, log-periodic antenna, etc. These antennas are effective for short-link communication unlike the resonant antennas which are effective for long-link communication.

4.0 THE YAGI ANTENNA

This antenna, named after its Japanese inventors Yagi and Uda, is made from materials with high electrical conductivity and reflecting ability. The antenna is very important because of its unidirectional pattern, high gain, broad bandwidth, higher terminal impedance, high directivity. It is used mainly as VHF and UHF television receiving antenna. It is made up of the folded dipole, reflectors and directors. Only the folded dipole is electrically connected to the feed line. The folded dipole, also called driven element, primarily serves as the feed point, and also helps to raise the antenna’s terminal impedance [5]. The folded dipole is usually resonant with the dipole length, which is half the wavelength applied to its feed point.

The director is usually 5% shorter than the folded dipole and located in front of it a distance less than 0.25λ. The directors can be made progressively shorter outwards to make the antenna taper in the direction of the transmitting antenna, making the antenna highly directive. Functionally, they direct electromagnetic energy towards the folded dipole, increasing the signal strength. Increasing their number and varying their lengths and spacing increase the directive gain and broad-band response of the antenna. They are usually shorter than the reflectors and act capacitively at high frequencies.

The reflectors are usually longer than the folded dipole by about 5% and are placed behind it. They act inductively at low frequencies. They increase the directive gain of the antenna by reflecting electromagnetic energy towards the folded dipole, reinforcing the signal strength in it. The efficiency of Yagi antenna, like all antennas, is dependent on such properties as reciprocity, radiation pattern, polarization, gain and bandwidth.

Reciprocity establishes that the properties of a resonant antenna used for reception are the same as when used for transmission. It is of fundamental importance to the determination of functionality and efficiency of any antenna, and permits measurements on a transmitting or receiving antenna [1].

Radiation pattern refers to the diverse special distribution of the energy radiated from or received by an antenna. There are various forms of radiation pattern: pencil, beam, split beam and multi-lobed pattern. The type of pattern chosen depends on what the antenna is expected to achieve. The radiation pattern of an antenna can affect its bandwidth, side-lobe level and gain. For the Yagi antenna, the radiation pattern consists of one main lobe lying in the forward direction along the axis of the array, with several very minor lobes in other directions.

Bandwidth is the range of frequencies over which an antenna will radiate or receive energy effectively [2], while its impedance remains reasonable within a given tolerance. The bandwidth of narrow-band antennas is given by

$$BW = (f_u - f_l)/f_c \qquad (3)$$

where f_l =lower frequency limit,f_u = upper frequency limit and f_c = centre frequency. For a broad-band antenna, $BW = f_u / f_l$ --- --- (4.0)

When the antenna power drops to half-power (3-dB) points, f_u and f_l have been reached and the antenna no longer performs satisfactorily.

The bandwidth of an antenna may be increased by tapering the antenna components, using thicker wires and combining multiple antennas into a single assembly, allowing the natural impedance to select the correct antenna. Yagi antenna can be made to have a larger bandwidth by tapering and increasing the number of directions.

Polarization is the orientation of the electric field in the radio wave with respect to the earth's surface, and is determined by the physical structure of the antenna and its orientation. Polarization may be vertical, horizontal or circular, with vertical and horizontal polarization being special cases of linear polarization depending on the orientation of antenna mounting [12]. For a television receiving antenna, polarization corresponds to the orientation of the radiating elements and antenna mounting. For this Yagi antenna, polarization is in the direction of the element axes. Signal strength is enhanced in line-of-sight communication when the transmitting and receiving antennas use the same polarization.

Gain is a measure of the ability of an antenna array to concentrate the radiated power in a given direction. A low-gain antenna radiates energy in all directions equally whereas a high-gain antenna preferentially radiates in a particular direction [11]. Gain is described using terms such as antenna gain, power gain, directivity or directive gain. The antenna gain of the Yagi antenna is greatly dependent on the dipole gain and the number of elements; and is given by:

$G = 1.66N$ --- --- --- --- --- (6)

where 1.66 is the dipole gain and N is the number of elements.

5.0 DESIGN CONSIDERATION

To design this high-gain antenna, aluminium rail of thickness, 2mm was chosen and used to make the elements. This choice was informed by the high electrical conductivity and resistance to corrosion of aluminium; the design was carried out in three stages involving the design of reflectors directors and folded dipoles with feeders.

A length of 45cm was made out of the aluminium and cut into six smaller lengths representing six reflectors. These elements were fixed to a v-shaped supporting bar and placed at the back of the folded dipole; they are inductive in operation.

To achieve optimum performance, the lengths of the directors were varied progressively outward from the folded dipole using a reduction factor of 0.1cm to 4cm. This makes the antenna taper in the direction of the transmitting antenna thereby increasing its directivity. A compact pair of ten directors carried on separate, parallel supporting bars connected by a short bar was designed for use. This arrangement is placed in front of the folded dipoles. The directors are capacitive in operation. Increase in the number of directors increases the gain of the antenna. The last stage was the design of the folded dipoles and feeders. The folded dipole is the major radiating element of the antenna. The dipole length was determined based on a frequency of 200MHz

From equation (6), wavelength, $\lambda = v/f$,

where the velocity of light, $v = 3 \times 10^8$m/s, wavelength = 1.5m

Therefore, dipole length = $\lambda/2 = 0.75$m

Due to electric field fringes, dipole correction requires that the dipole length, D becomes:

$D = 0.75 - (5/100 \times 0.75) = 0.75 - 0.0375 = 0.713$m

Accordingly, two lengths of aluminium, 143cm each, were cut and folded to have two folded dipoles designed as symmetric conductors with two ends of opposite potentials, and are meant to increase the terminal impedance. Their terminals are housed in the feeder, a non-conducting material, meant to prevent their inter-connection as well as protect them from moisture.

Implementation Procedure

The antenna was constructed using aluminium rail for antenna elements, 2cm-squared metal rod as boom, hacksaw for cutting the materials, gimlet for drilling holes, screw nails for fastening the elements to the boom, measuring tape, welding machine, 75-ohm coaxial cable as transmission line and feeders to house the terminals of the folded dipoles.

The elements were first measured, cut out of the aluminium rail and holes drilled at their mid-points. Then the boom was constructed. The boom was made in two parts and welded together. The first part was the reflector boom. For this purpose, a length of 40cm was cut out of the metal rod, bent into a V-shape and holes made on it for the reflectors. This essentially forms a reflector unit of six reflectors (R1- R6). The second part was the director boom. Two lengths, each 86cm, were cut from the metal rod and welded, one over the other. Using metal supports, holes were then drilled on them and the directors were screwed into their appropriate positions. These two parts were welded together and painted to form a single composite pair of ten directors (D1-D10).

Lastly, the feeders were fixed to the director booms with screw nails, one on each director boom; and the terminals of the folded dipoles were then fixed to the inside of the feeders. With the feeders and folded dipoles in place, the reflector and director units were fixed to the back and front of the dipoles respectively. Finally, the folded dipoles were connected together by means of a coaxial cable which serves as the transmission line, coupling the antenna to the television and transmitting signals directly to the television from the terminals of the folded dipoles. The antenna has a gain of 16.6dB .

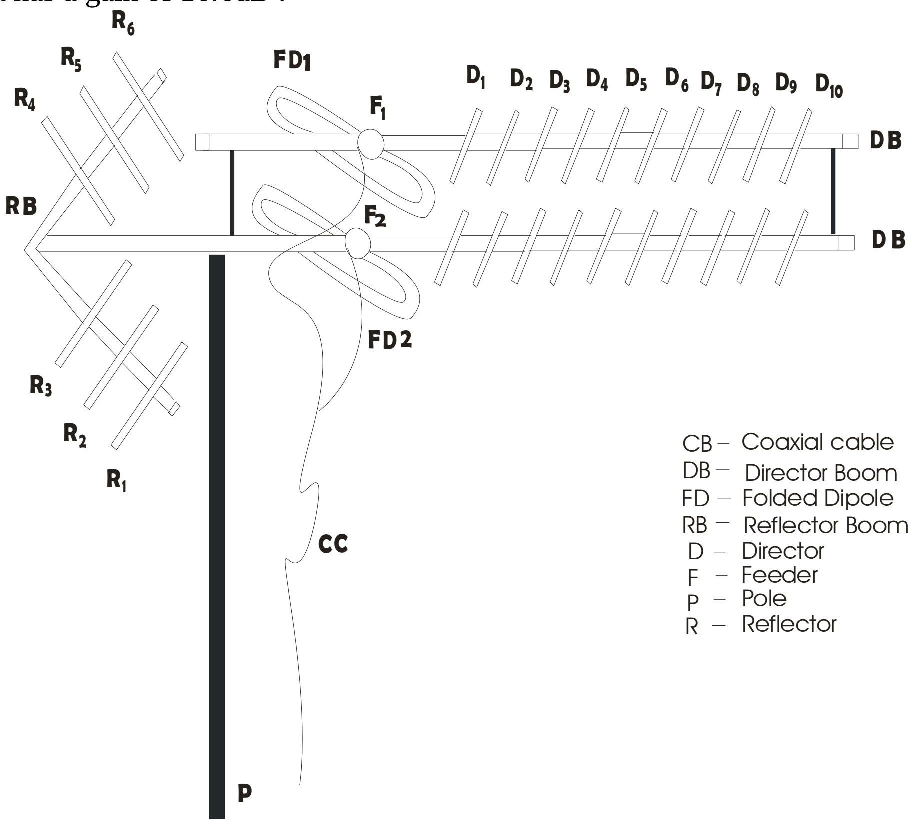

Figure 1: The Compound Yagi Antenna

Dimensions and Spacing of Antenna Elements

Element Length		**Element Spacing**	
Total boom length	212cm		
Reflector boom length	40cm	Reflector – Reflector	12.00cm
Director boom length	86c	Director – folded dipole	7.30cm

Folded dipole	143cm	D1 –D2	7.70cm
Reflectors (R1 = R2-----=R6)	45cm	D2 – D3	7.70cm
Directors		D3–D4	7.5cm
D1	30.20cm	D4 – D5	7.8cm
D2	30.10cm	D5 – D6	7.8cm
D3	30.00cm	D6 – D7	7.9cm
D4	29.90cm	D7 – D8	8.2cm
D5	29.89cm	D8 – D9	7.7cm
D6	29.88cm	D9 – D10	7.7cm
D7	25.30cm	**Antenna parameters**	
D8	23.00cm	Design frequency(f)	200MHz
D9	22.00cm	Wavelength (λ)	150cm
D10	20.00cm	Dipole Length (D)	71.50cm
		Antenna Gain	16.7dB

Following the successful construction of the antenna it was mounted on a pole about 11m tall for performance test with a TV receiver at Hanala Motel and Kogi State University (KSU) staff quarters for several hours. The test showed that sharp pictures and audible sound were produced for channels in the UHF and UHF bands. Results of the test are shown in table 2.

RESULTS AND DISCUSSION

Table 2: Experimental Results

Channel	Frequency (MHz)	Dist. (Km)	LOCATION1: HANALA MOTEL Audio Quality	Video Quality	LOCATION 2: KSU STAFF QUARTERS Audio Quality	Video Quality
NTA6(VHF) ANYIGBA	182.25	2.0	Very Audible	Very Sharp	Very Audible	Very Sharp
NTA12(VHF) LOKOJA	224	119.0	Very Audible	Very Sharp	Very Audible	Very Sharp
NTA23(UHF) ANKPA	487	58.0	Very Audible	Very Sharp	Audible	Sharp
NTA8(VHF) ENUGU	196	250.0	Audible	Sharp	Audible	Sharp
CTV55(UHF) LOKOJA	742.45	119.0	Fairly Audible	Blurred	Fairly Audible	Blurred
OSRC27(UHF) AKURE	486.45	305.0	Audible	Fairly Sharp	Audible	Fairly Sharp
NTA10(VHF) MAKURDI	209.45		Very Audible	Fairly Sharp	Very Audible	Fairly Sharp

The best material to use for constructing the Yagi antenna is a conducting material such as aluminium whose high electrical conductivity and reflecting ability have ensured excellent gain in this work. Also, the geometric dimensions of the antenna greatly increased the gain. The lengths of the antenna elements which were made to be harmonics of the resonant frequency ensured that current distribution in the elements and coupling are in phase. This made sure that maximum power was delivered to the TV receiver. Increasing the number of directors was observed to have increased the directive gain greatly. Modifications such as double folded dipole, compound director unit and the V-shaped reflector unit have been discovered to have greatly enhanced the directive gain and overall performance of this antenna. The double folded dipole increased the terminal impedance appreciably, ensuring a very good match to the transmission line.

Furthermore, it was observed that improper impedance matching and antenna orientation resulted in no signal or poor signal strength. Appropriate coaxial cable must be used to couple the dipole terminal to a TV receiver to ensure maximum power delivery to the TV receiver. The antenna must also point in the direction of the transmitting antenna.

Experimental results have shown weather conditions such as humidity, rainfall, sunshine, frost, fog, dew etc. to affect the efficiency of the antenna a great deal. Rainfall causes attenuation in the UHF band . Fog and sunny weather conditions cause great attenuation in both UHF and VHF bands due to scattering and high ionization level in the ionosphere. Also, topographic features like mountains and valleys block and absorb radio signals; these can be reduced greatly by using tall poles to increase the altitude of the antenna. Performance test has proven that the taller the pole the better the quality of reception.

Results of tests using an 11m pole revealed excellent performance in the VHF and UHF bands. This compound antenna gave a better performance than a single, simple Yagi antenna. Sharp picture and audible sound were received from NTA 12, Lokoja; NTA 23, Ankpa; NTA 8 Enugu and others, attesting to the high-gain performance of this antenna. Better signal was received from NTA 10, Makurdi; OSRC 27, Akure and CTV55, Lokoja on extremely cool and calm days. In all cases weather changes affected the results. NTA Enugu and NTA Makurdi lose colour when the intensity of the sun goes high, but regain colour in the morning and evening hours when the weather gets calm and cool.

CONCLUSION

Results of tests have shown that the high-gain Yagi antenna is broad-band in operation covering channels in VHF and UHF bands. It is reliable and effective for production of high fidelity sound and picture in TV receivers when properly matched to a feeder cable. It is also cost effective and serves as a good substitute for any imported one.

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