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Development of an Optimum Beamforming Strategy for Outdoor Communication in Millimeter Wave Wireless Sensor Network

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Abstract—**The emerging future wireless sensor networks (WSNs) will utilize the millimeter-wave (mmWave) spectrum for wireless communication. The essence is to avoid spectrum crunch and mitigate bandwidth-hungry applications and services (traffic congestion) in WSNs by exploiting the underutilized spectrum between the 30 GHz and 300 GHz bands, respectively. Since mmWave has a short wavelength, deploying it in WSNs for remote monitoring applications in outdoor environments is still a challenge due to issues of shadowing, blockage effects, and propagation losses associated with atmospheric effects due to rain and oxygen. This paper proposed an optimum beamforming strategy to be employed in mmWave WSNs for remote monitoring applications to offset the additional propagation losses in mmWave outdoor environments through a two-split mix of analog beamforming and hybrid analog/digital beamforming. Also, signal transmission and reception through amplify-and-forward (AF) relay-assisted mmWave WSN is proposed for compensation of the signal fading effect due to blockages. This will ensure greater reliability in the 60 GHz underutilized unlicensed mmWave band when employed in mmWave WSNs for remote temperature monitoring in outdoor environments.**

Keywords—**wireless sensor network (WSN), millimeter wave (mmWave), beamforming, amplify and forward (AF) relay, remote monitoring.**

I. INTRODUCTION

Wireless sensor networks (WSNs) are emerging as highly promising technologies with widespread applications in various fields including industry, environment, agriculture, healthcare, security, transportation systems, and the military. WSNs are composed of a network of spatially dispersed sensors along with one or more sink nodes, which are also referred to as base stations. These sensors, distributed throughout the network, gather data from the surrounding environment and transmit it wirelessly to the sink nodes. The sink nodes serve as central hubs or collection points, where the gathered data is processed, analyzed, and further transmitted to a central monitoring system or end-user applications. This composition of WSNs enables the seamless integration of sensing capabilities with wireless communication, providing a versatile and efficient solution for monitoring and control applications in a wide range of domains. A sensor node is a self-contained, small device that contains sensors as well as other components for processing and delivering sensory data. A sensor node produces data by sensing physical factors and then finally sends this data to a central location. Sensors generate sensory data and continuously monitor physical factors, including temperature, vibration, and motion. A sensor node may act as a data router and data originator simultaneously. On the other hand, a sink gathers information from sensors. For instance, when sensors detect the occurrence of important events in an event monitoring application, they must communicate that data to the sink(s). Direct connections, the Internet, satellite, or any kind of wireless link are all possible methods for the sink and the end user to communicate [1]. Currently, many applications rely on WSNs for synergizing information; hence, many devices are being connected to various WSNs for various applications. Global data traffic being generated by the increasing number of devices in WSNs doubles annually, creating a lot more burden on the current radio frequency (RF) spectrum, which is already facing a spectrum crunch. The trend is predicted to continue increasing within the next decade, with trillions of devices connected to the RF WSNs [1].

Due to the predicted RF spectrum congestion and shortage, millimeter-wave (mmWave) wireless communication is being well-thought out as a valuable enabling technology to support WSNs and other technologies as highlighted in [2, 3]. The basis for the next generation of wireless communication will be mmWave [4, 5]. MmWave introduces new capabilities that will allow the implementation of applications like the Internet of Things (IoT), data centers, autonomous vehicles, and virtual and augmented reality.

The mmWave band (3GHz to 300GHz) has attracted much attention from research groups as it presents a perfect transmission medium for the next generation of wireless communication [1]. In several indoor

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applications, the mmWave band has been successfully utilized as high data rate media. The 60GHz band, for instance, was employed in the early production of mmWave commercial applications in the WPAN (wireless personal area network), which led to the IEEE 802.15.3c standard's publication [5]. In order for the mmWave technological revolution to occur, many possibilities and challenges that are associated with deploying mmWave bands still need to be investigated and addressed. Deploying mmWave WSNs for remote monitoring in outdoor environments remains challenging. Measurements in outdoor environments resulted in short mmWave wireless communication links due to shadowing and blockage effects, including propagation losses in the atmosphere due to rain and oxygen [6, 7].

This paper proposed an optimum beamforming strategy to be employed in mmWave WSNs for remote monitoring applications in outdoor environments, with a focus on remote temperature monitoring as the physical phenomenon. At mmWave frequencies, the antenna size becomes smaller, so more elements can be added into an array of antennas. Increasing the directivity through beamforming techniques could extend the coverage of a mmWave link [8, 9]. Moreover, in the context of short-range mmWave wireless connections, the utilization of relays functioning as micro base stations will play a critical role in expanding the reach of mmWave links [10].

There are different types of beamforming techniques that will be discussed in this subsection.

A. Narrowband Versus Wideband Beamforming

Beamforming can be classified according to the bandwidth of the signal: narrowband vs. wideband beamforming. Beamforming in narrowband can be attained by the linear combining of array signals. Conversely, when wideband signals are involved, for effective operation, additional signal processing must be deployed [11]. Most wireless applications are currently fixated on narrow-band beamforming. Though, for future applications of wireless communication in the underutilized 60 GHz mmWave band, wideband beamforming becomes very important.

B. Adaptive Versus Switched Array Beamforming

TABLE I. EVALUATION OF SWITCHED AND ADAPTIVE BEAMFORMING [14]

Parameter	Adaptive beamforming	Switched beamforming
Capacity and coverage	Covers a larger area and more uniform at the same power level as compared to switched beamforming.	Better capacity and coverage with improvement ranging from 20% to 200%.
Elimination of interference.	A more comprehensive interference rejection is offered.	Suffers when differentiating between an interferer signal and the desired signal.
Cost and complexity.	-Implementation is difficult. -It is expensive. -Highly complex since it requires a lot extra time and more precise algorithms for beam steering and nulling.	-Implementation is easy in an already existing system network. -It is inexpensive. -Uses simple algorithms when selecting beams.

Schemes in beamforming can also be categorized generally as adaptive or switched array. A system employing a switched beam is dependent on a fixed beamforming network and a switching network that chooses an appropriate beam to produce the signal desired. Fixed beamforming can be employed using a matrix composed of crossovers, phase shifters, and hybrid couplers, referred to as the Butler matrix [12]. Adaptive array systems, on the other hand, have the capability of formulating for each terminal a singular beam [13]. Table I illustrates the comparison between switched beamforming and adaptive beamforming.

C. Analog versus Digital Beamforming

Techniques of beamforming can also be classified as analog and digital beamforming. Analog beamforming comprises fixed phase shifters and hybrid matrices, and the main concept behind it is the control of the phase of each transmitted signal by utilizing low-cost phase shifters. Digital beamforming comprises many utilities, which include programmable antenna radiation pattern control, DOA estimation, adaptive beam, and null steering for enhancing SINR [15, 16]. Implementing digital beamforming in mmWave systems, conversely, is not suitable because at the baseband, beamforming is implemented traditionally, which aids in controlling signal amplitude and phase [17]. Therefore, digital beamforming requires up-conversion of the processed signal carrier frequency after RF chain crossover. The RF chain comprises DACs, mixers, and power amplifiers. The RF chain responses are then combined with the elements of the array antenna. Each element of the antenna array, however, has a dedicated RF chain, which becomes expensive to realize for mmWave systems due to the necessary bulky number of antenna elements. Application of analog beamforming is performed by utilizing inexpensive phase shifters; hence, it is more cost-effective compared with digital beamforming. Analog beamforming, conversely, has lesser performance compared with digital beamforming due to the inflexible phase shifters' amplitudes [15].

D. Hybrid Beamforming

Digital beamforming needs a separate RF chain per antenna element [18, 19] leading to complex architecture with high consumption of power and high RF chains cost. Therefore, hybrid beamforming, which operates in the analog and baseband digital domains, is preferred, and different hybrid architectures have been proposed by several research studies with the aim of reducing the RF chain number through a combination of analog RF beamforming and baseband digital beamforming techniques called hybrid forming techniques. Hybrid beamforming appears to be more suitable for mmWaves because the number of RF chains can be limited, making it less than the number of antenna elements. Architectures of hybrid beamforming can be categorized as fully connected, where each RF chain has a connection to all antenna elements, and partially connected, where each RF chain has a connection to a given set of antenna elements. The beamforming gain for a fully connected hybrid beamforming architecture is greater than for the partially connected hybrid beamforming architecture [20, 21]. There are a few research papers in the literature on hybrid beamforming. Hybrid beamforming architectures were categorized in [22] according to the channel state information required at BS for downlink transmission, carrier frequency range, and complexity. Their work concluded that none of the hybrid beamforming architectures can give the finest trade-off between performance and complexity, and as such, for the best performance, the architecture needs to be very dynamic based on the channel conditions and application. Hybrid beamforming was classified in [23] based on the analog beamforming components, which can be implemented using electronic switches, digitally controlled phase shifters, or lens antennas. Interference between data streams can be eliminated by the digitally controlled phase shifters, however, they suffer from quantization error and high-power consumption. Electronic switches exploit the mmWave channel sparse nature and instead of optimization of all quantized phase values, selection of only a subset of antennas is done. Lens antennas are utilized at the front-end for analog beamforming. The paper did not take other components, such as switches or phase shifters, into account in the different hybrid beamforming structures. None of the papers aforementioned investigated the optimum beamforming technique suitable in mmWave WSN for remote temperature monitoring in the outdoor environment. This study therefore proposes the achievement of better beamforming in a mmWave WSN for remote temperature monitoring in an outdoor scenario through a two-split mix between analog beamforming and hybrid analog/digital beamforming.

E. Relay Networks

The large size and directivity gain of antenna arrays can improve the mmWave system quality. However, these solutions cannot be effective on their own. Deploying one or more relays in a mmWave communication link is promising to further alleviate the penetration losses, which result from propagation losses and blockage [24, 25]. Considering the proposed small cells for mmWave communication architecture and the utilization of dense access points, relaying becomes of great importance in providing coverage extension [26]. Several research studies have considered relay-assisted wireless communication links as the basis for the next generation of wireless communication architectures. At mmWave frequencies, propagation characteristics become worse, hence, the relay network implementation becomes more essential [27]. This study therefore assumes signal transmission and reception through a relay-assisted mmWave WSN for remote temperature monitoring in an outdoor environment for compensation of the signal fading effect as a result of strong shadowing and propagation losses and to provide reliable mmWave WSN communication. It is against the background discussed above that this study seeks to develop an optimum beamforming strategy for outdoor communication in mmWave WSN for remote monitoring applications, with an emphasis on temperature monitoring in outdoor environments.

MmWave communication is expected to meet the current rising need for connections and traffic in WSNs by exploiting the huge frequency band (30GHz to 300GHz) of the electromagnetic spectrum [1]. MmWave communication has been utilized successfully in indoor environments. However, utilization of mmWaves in outdoor environment still remains a huge challenge. Various research studies involving measurements in outdoor environments showed additional signal propagation losses (due to oxygen and rain). In addition, frequent interruptions as a result of shadowing and blockage are due to obstacles blocking the mmWave signal path, leading to short mmWave communication ranges [7]. Hence, there is a need to evaluate the existing beamforming techniques in order to develop an optimum beamforming strategy for mmWave communication in WSN that can be deployed in outdoor environments for remote monitoring purposes.

The rest of this paper is organized as follows: Section II discusses the related studies and literature on beamforming in mmWave environments. Section III presents the mmWave WSN conceptual model for remote monitoring in outdoor environments. Section IV presents the numerical results and a discussion of the results obtained. Section V concludes the paper, suggesting recommendations and prospects for the future extension of the study.

II. RELATED WORK

Beamforming techniques have been researched in standards that include IEEE 802.15.3c [28] (utilized for indoor WPAN), IEEE802.11ad [29], WLAN, and Wireless HD, focused on uncompressed high-definition television streaming. Techniques of beamforming have been more specifically proposed for office indoor environments with applications in few meter ranges [30]. Beam search (one-sided) utilizing codebook beamforming has also been deployed in WLAN for the establishment of initial alignment of the beam between large antenna arrays [31]. The methods used for beamforming utilized for indoor set-ups, however, do not simply extend for outdoor set-ups where propagation of mmWaves to longer distances is significantly impaired by severe path loss, atmospheric absorption, shadowing, and blockage, and therefore a much larger and optimum beamforming gain is required in outdoor scenarios for WSNs for remote temperature monitoring. Some of the research works on mmWave beamforming, which proposed a beam alignment technique utilizing hierarchical beam codebooks and subspace sampling for mmWave beamforming for providing small cell networks access and backhaul [32]. The authors of [33, 34] focused on MIMO systems and beamforming approaches. Cordeiro and Akhmetov *et al.* [30] presented an investigation of the MIMO relay network beamforming technique. Vouyioukas [33] reviewed the beamforming techniques for cognitive networks in MIMO systems, where the authors used strategies of cooperative beamforming and distributed jointing that were built on genetic algorithms, neural networks, and game theory to evaluate the cognitive beamforming techniques. Lu and

Li *et al.* [20] worked centered on the utilization of beamforming techniques for mmWave communications. Molisch *et al.* [23] presented a signal processing overview for mmWave communication systems. The aforementioned research works investigated in detail the significance of beamforming for mmWave systems. The works, however, did not discuss the optimal beamforming techniques that could be employed in mmWave WSNs for remote temperature monitoring applications in outdoor environments. This study therefore proposed an evaluation of the existing beamforming techniques to determine the categories that can be adopted for mmWave WSNs for remote temperature monitoring in an outdoor environment scenario, the modeling of the optimum mmWave beamforming strategy, and the analysis of the proposed optimum mmWave beamforming strategy.

The results that were obtained in the research study were compared to the research works in [8, 34], where measurements were done in mmWave outdoor environments. Keusgen and Weiler *et al.* [8] presented the motivation for the new mmWave cellular systems, measurement hardware, and methodology. It stated that little is known about cellular mmWave propagation in densely populated outdoor and indoor environments, and therefore the obtaining of such information is very vital for the operation and design of future generation cellular networks that will utilize the mmWave spectrum. A variety of measurement results showed that mmWave frequencies can be utilized when steerable directional antennas are employed at base stations and mobile devices. Measured atmospheric loss in the mmWave outdoor environment due to rain and oxygen absorption resulted in 18 dB/km. The authors of [34] investigated the scattering and propagation behavior of the 60 GHz mmWave signals in the outdoor environments at 147 meter travel distance for a ground link, i.e., light pole-to-light pole, and at 98 meter travel distance for an aerial link, i.e., rooftop-to-rooftop. The motivation of the study was that mmWave high attenuation significantly reduces the areas of coverage, and hence it is very critical to study the mmWave propagation characteristics in multiple scenarios of deployment. Measurements were conducted by using Facebook Telegraph radios, and the results included the received power, SNR, path loss, and root mean square delay spread for all the directions of beamforming supported by an array of antennas. A strong line of sight (LOS) propagation was observed to exist in both the aerial and ground links. Path loss measurements at 60 GHz revealed a path loss of 110.2 dB for an aerial link (rooftop-to-rooftop) at a 98-meter travel distance and a path loss of 117.05 dB for a ground link (light pole-to-light pole) at a 147-meter travel distance using phased array antennas.

III. MMWAVE WSN CONCEPTUAL MODEL FOR REMOTE MONITORING OUTDOOR ENVIROMENT

mmWave bands present many advantages that could be exploited in WSNs for remote temperature monitoring applications. The many available gigahertz of underutilized spectrum in mmWave bands [35] can be exploited to solve the current RF spectrum crunch. Additionally, the nature of LOS millimeter wave communication can also be exploited so as to control the interferences between systems. However, mmWave WSNs for remote monitoring in outdoor environments will require large directional gains and the deployment of more relays compared to remote temperature monitoring WSNs with lower frequencies in an attempt to combat the high path loss, additional atmospheric losses, shadowing, and blockage. To achieve the required large directional gain in mmWave WSN for remote temperature monitoring in outdoor environments, deployment of phased array antennas or a large physical aperture must be done. However, the deployment of a large physical aperture is not feasible, as its installation and maintenance would be very costly. Conversely, the deployment of phased-array antennas, which are capable of providing large beamforming gains, and the elements in the antenna array is feasible thanks to the mmWave small wavelength, The conceptual model of the relay-assisted mmWave WSN for remote temperature monitoring in an outdoor environment is presented in Fig. 1, comprising fixed, non-cooperative remote wireless sensor nodes that are geographically distributed in a mmWave outdoor environment with blockages represented by buildings and trees, rain, and oxygen interruptions. MmWave communication between the sensor nodes and fusion center is assisted by a single AF relay to enable the mmWave WSN communication links and further alleviate the penetration losses that result from strong shadowing and obstacles that block the mmWave signal path. Relaying becomes of great importance for a reliable mmWave WSN for remote temperature monitoring in an outdoor environment by providing mmWave link coverage extension. A single fusion center point is considered in the conceptual model for mmWave WSN for remote temperature monitoring in outdoor environments as the central location where all the sensor data is collected for monitoring purposes.

A. *Proposed Optimum Beamforming Model*

The study proposed an optimum beamforming strategy in mmWave WSN for remote temperature monitoring in an outdoor environment. A conceptual model for mmWave WSN for remote temperature monitoring in outdoor environments is presented in which optimum beamforming is achieved through employing analog and digital beamforming combinations. Different levels of signal processing are required at the source sensor nodes, relays and fusion center or destination. This study proposed a two-split optimum beamforming strategy where the source sensor node-to-relay mmWave transmission utilizes hybrid analog/digital beamforming with multiple RF chains, while the AF-to-fusion center/destination mmWave transmission utilizes analog beamforming with a single RF chain. The two-split optimum beamforming model works on directing the mmWave signals in order to obtain higher beamforming gain to overcome the additional propagation losses that occur during mmWave signal transmission from source sensor node to AF relay and also during transmission from AF relay to fusion center. The two-split optimum beamforming model is presented consisting of a single sensor node communicating with a single fusion center or destination through a single AF relay. The source sensor node is equipped with N_T ULA antenna elements and N_{RF}^{T} RF chains. The fusion center/destination has N_D ULA antenna elements and N_{RF}^{D} RF chains. The AF relay has N_R and N_R^T ULA antenna elements on the receive and transmit sides respectively and utilizing a single RF chain. The source sensor node-to-fusion center/destination connection via one stream is assumed in this study.

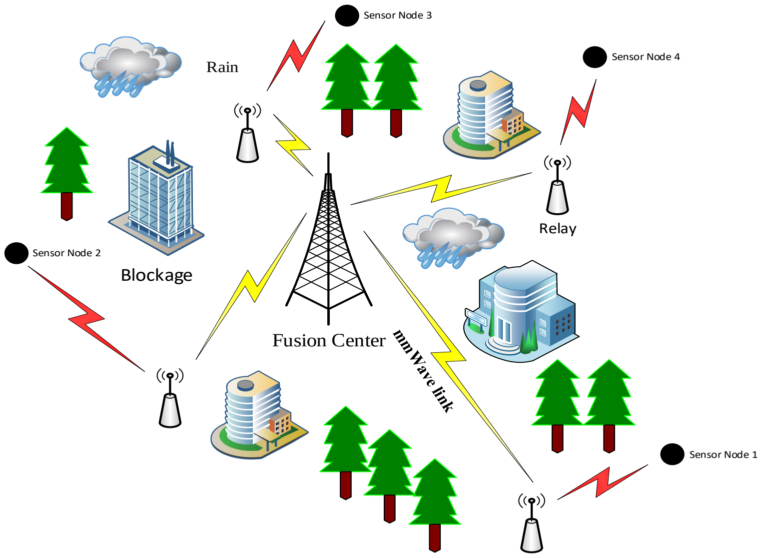

Figure 1. Conceptual model for mm Wave WSN for remote temperature monitoring in outdoor environments.

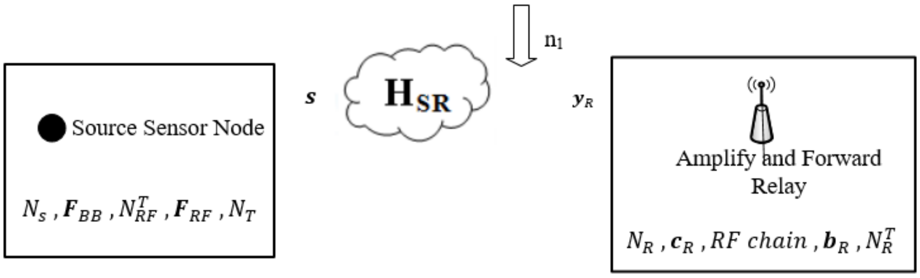

Figure 2. Source sensor node-to-AF relay beamforming strategy.

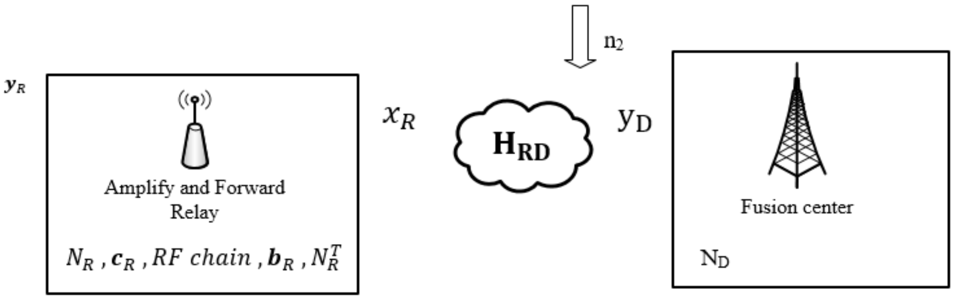

Figure 3. AF relay-to-fusion center/destination beamforming strategy.

B. *Source Sensor Node-to-AF Relay Beamforming Strategy*

Based on the presented conceptual model in Fig. 1 for mmWave WSN for remote temperature monitoring in outdoor environment, much signal processing is required at the source node than at the relay. Therefore, for optimum beamforming, the study proposed transmission from the source sensor node-to-AF relay to employ a hybrid analog/digital beamforming strategy as shown in Fig. 2. An attempt to overcome propagation losses which arise usually in such outdoor mmWave environments in order to obtain a higher beamforming gain that can extend the source sensor node-to-relay mmWave point-to-point link. The source sensor node has N_T antennas and N_{RF}^{T} RF chains. The AF relay on the other hand, is equipped with N_R antenna elements on the receive side and a single RF chain. Using multiple RF chains, both the source sensor node and fusion center/destination processes the signal in the hybrid analog and digital domains. During the source sensor node-to-relay transmission, the source sensor node applies digital precoding/combining $\boldsymbol{F}_{BB}$ followed by analog precoding

$\boldsymbol{F}_{RF}$ on the source sensor node data stream N_s. Source sensor node transmits signal $\boldsymbol{s}$ through mmWave link $\boldsymbol{H}_{SR}$ and signal $\boldsymbol{y}_R$ is received at the AF relay taking into account the additive white gaussian noise $\boldsymbol{n}_1$ at the AF relay.

C. Relay-to-Fusion Center Beamforming

At the AF relay, less signal processing is required compared to that at the source node. Therefore, for optimum beamforming, the study proposed transmission from the AF relay-to-fusion center/destination to employ an analog beamforming strategy as shown in Fig. 3 in an attempt to reduce on the system complexity and cost.

The AF relay, on the other hand, is equipped with N_R and N_R^T ULA antennas and a single RF chain. The AF relay has an analog combiner $\boldsymbol{c}_R$ to receive the source sensor node signal and employ analog precoder $\boldsymbol{b}_R$ to transmit the received source sensor node signal. Fig. 3 illustrates the AF relay-to-fusion center/destination analog beamforming strategy. The AF relay transmits signal $\boldsymbol{x}_R$ through mmWave link $\boldsymbol{H}_{RD}$ and signal $\boldsymbol{y}_D$ is received at the fusion center taking into account the additive white gaussian noise $\boldsymbol{n}_2$ at the fusion center.

D. mmWave Link Model

Measurements performed in mmWave outdoor environment at mmWave frequencies 28 GHz and 72 GHz revealed that there is normally limited scattering [8, 36] and in order to integrate this effect, this study adopts a geometric link model where the propagation link is assumed to be a summation of L scattering clusters, each cluster contributing to P uniformly distributed propagation paths to the link [37-39] and complex path gains which follow a Gaussian distribution of equal variances. ULAs of inter-antenna elements separation $d = \frac{\lambda}{2}$ is assumed at the TX and RX and the link matrix is expressed as:

$$\boldsymbol{H}_{SR}\{\boldsymbol{H}_{RD}\} = \frac{1}{\sqrt{PL}}\sum_{l=1}^{L}\sum_{p=1}^{P}\alpha_{pl}\,\boldsymbol{a}_r\left(\theta_r^{pl}\right)\boldsymbol{a}_t^H\left(\theta_t^{pl}\right) \quad (1)$$

where, α_{pl} is the complex small-scale fading gain for the p^{th} sub-path in the l^{th} cluster. θ_{pl}^t and θ_{pl}^r are angles of departure and arrival (AoD/AoA) respectively. α_{pl} is complex Gaussian variables. $\boldsymbol{a}_t^H\left(\theta_t^{pl}\right)$ and $\boldsymbol{a}_r\left(\theta_r^{pl}\right)$ vectors are the array response vectors at the transmitter and receiver, respectively. Noise variance $\sigma_{n_1}^2 = \sigma_{n_2}^2$ is assumed. The mmWave link coverage for both the source sensor node-to-AF relay transmission and AF relay-to-fusion center mmWave link is specified as $\theta \in \{\frac{-\pi}{2}, \frac{\pi}{2}\}$. Array response vector $(\boldsymbol{a})$ will be defined as:

$$\boldsymbol{a}(\theta) = \frac{1}{\sqrt{A}}[1 \;\; e^{j2\pi\frac{d}{\lambda}\sin\theta} \;\; \ldots \;\; e^{j2\pi(A-1)\frac{d}{\lambda}\sin\theta}]^T \quad (2)$$

where, d is the space between the antenna elements, A is the number of antennas, and λ is the wavelength.

The two-split optimum beamforming strategy for mmWave transmission from the source sensor node-to-fusion center/destination is then analyzed based on the beamforming gain produced as the figure of merit. The beamforming gain produced is also examined based on the number of antenna elements used and the number of RF chains used. The study is based on research works in [8] and [34] in an attempt to extend mmWave link coverage in a mmWave based WSN for remote monitoring applications in outdoor environments by using a two-split optimum beamforming strategy to direct mmWave sensor node data signals to produce a large beamforming gain which can offset the additional propagation losses which greatly affect mmWave transmission.

IV. NUMERICAL RESULTS AND DISCUSSION

A two-split optimum beamforming strategy suitable for outdoor communication in mmWave WSN for remote temperature monitoring was developed using Matlab. The system setup considered transmission through a single source sensor node to a single fusion center/destination through a single AF relay. The source sensor node utilized hybrid analog and digital beamforming strategy for signal transmission whereas the AF relay utilized analog beamforming strategy for signal transmission to the fusion center. The mmWave link from source sensor node-to-AF relay and from AF relay-to-destination/fusion center was modelled using L scattering clusters, each cluster contributing to a single uniformly distributed random AoA and AoD ray and considered to have equal power. ULAs of inter-antenna elements separation $d = \frac{\lambda}{2}$ was assumed. Noise variance $\sigma_{n_1}^2 = \sigma_{n_2}^2 = \sigma_n^2$ was assumed and SNR $= \frac{\rho}{N_S\,\sigma_n^2}$. The number of RF chains $N_{RF}^T \in \{1, 3, 6\}$, and the number of antenna array elements $N_T, N_R, N_R^T, N_D \in \{8, 16, 32\}$ are other additional parameters that were used in the modelling of the two-split optimum beamforming strategy. The AF relay was assumed to be of equal separation distance of 1000 meters from the source sensor node and fusion center/destination.

A. Source Sensor Node-to-AF Relay Hybrid Analog and Digital Beamforming System

During the source sensor node-to-AF relay mmWave transmission, the source sensor node applied $N_s \times N_{RF}^T$ digital precoding/combining $\boldsymbol{F}_{BB} = [\boldsymbol{f}_1^{BB}, \boldsymbol{f}_2^{BB}, \ldots, \boldsymbol{f}_{N_{RF}^T}^{BB}]$ followed by $N_T \times N_{RF}^T$ analog precoding $\boldsymbol{F}_{RF} = [\boldsymbol{f}_1^{RF}, \boldsymbol{f}_2^{RF}, \ldots, \boldsymbol{f}_{N_{RF}^T}^{RF}]$ on the source sensor node data stream. The AF relay received signal was given as:

$$\boldsymbol{y}_R = \boldsymbol{H}_{SR}\,\boldsymbol{F}_{RF}\,\boldsymbol{F}_{BB}\,s + \boldsymbol{n}_1 \quad (3)$$

where, $\boldsymbol{s}$ is $N_s \times 1$ source sensor node transmit signal. $\boldsymbol{H}_{SR}$ is $N_R \times N_T$ source sensor node-to-AF relay mmWave link matrix. $\boldsymbol{n}_1$ is the additive white gaussian noise at the AF relay with a covariance matrix $R_{n_1} = \sigma_{n_1}^2\,\boldsymbol{I}_{N_R}$.

The optimum beamforming gain produced was given as:

$$G_{SR} = argmax\left\{\sum_{n=1}^{L}\left|\acute{w}_R \times \boldsymbol{H}_{SR_n} \times w_T\right|^2\right\} \tag{4}$$

where, G_{SR} is the optimum beamforming gain, $\boldsymbol{H}_{SR_n}$ is a mmWave channel matrix of dimension $N_R \times N_T$, w_R is a column matrix of AF relay receive antenna coefficients of dimension $N_R \times 1$, w_T is a column matrix of source sensor node transmit antenna coefficients of dimension $N_T \times 1$, and L are number of clusters.

B. AF Relay-to-Destination/Fusion Center Analog Beamforming System

The system considered no delay in signal processing at the AF relay. The AF relay transmitted signal was given as:

$$\boldsymbol{x}_R = \boldsymbol{b}_R\, \boldsymbol{c}_R^H\, \boldsymbol{y}_R \tag{5}$$

where, $\boldsymbol{x}_R$ is the AF relay transmit signal, $\boldsymbol{b}_R$ is the analog precoder, $\boldsymbol{c}_R^H$ is the analog combiner, and $\boldsymbol{y}_R$ is the AF relay received signal.

The fusion center/destination observed the source sensor node signal transmitted by the AF relay. The signal received at the fusion center was given as:

$$\boldsymbol{y}_D = (\boldsymbol{H}_{SR}\, \boldsymbol{F}_{RF}\, \boldsymbol{F}_{BB}\, s\, \boldsymbol{b}_R\, \boldsymbol{c}_R^H\, \boldsymbol{H}_{RD} + \boldsymbol{H}_{RD}\, \boldsymbol{b}_R\, \boldsymbol{c}_R^H\, \boldsymbol{n}_1) + \boldsymbol{n}_2 \tag{6}$$

where, $\boldsymbol{H}_{RD}$ is $N_D \times N_R^T$ AF relay-to-fusion center/destination mmWave link matrix and $\boldsymbol{n}_2$ is the additive white gaussian noise at the fusion center/destination with a covariance matrix $R_{n_2} = \sigma_{n_2}^2\, \boldsymbol{I}_{N_R}$.

The optimum beamforming gain produced was given as:

$$G_{RD} = argmax\left\{\sum_{n=1}^{L}\left|\acute{w}_D \times \boldsymbol{H}_{RD_n} \times w_R^T\right|^2\right\} \tag{7}$$

where, G_{RD} is the optimum beamforming gain, $\boldsymbol{H}_{RD_n}$ is a mmWave channel matrix of dimension $N_D \times N_R^T$, w_D is a column matrix of destination/fusion center receive antenna coefficients of dimension $N_D \times 1$, w_R^T is a column matrix of AF relay transmit antenna coefficients of dimension $N_R^T \times 1$, and L is number of clusters.

The array size of the source sensor node-to-AF relay array had a much greater influence on the beamforming gain translating into improved spectral efficiency as shown in Fig. 4. The source sensor node-to-AF relay hybrid analog and digital beamforming analysis showed significant improvement in the beamforming gain achieved. It separated the optimization process into analog and digital domains. The criterion that was used in the modelling of the source sensor node-to-AF relay was to limit the number of RF chains N_{RF}^T ensuring that it is less than the number of array antenna elements N_T. Increasing the number of RF chains in the system showed a positive impact on beamforming gain produced and spectral efficiency achieved as shown in Fig. 5 but this comes at the expense of energy consumption as the larger the number of RF chains, the lower the power saving.

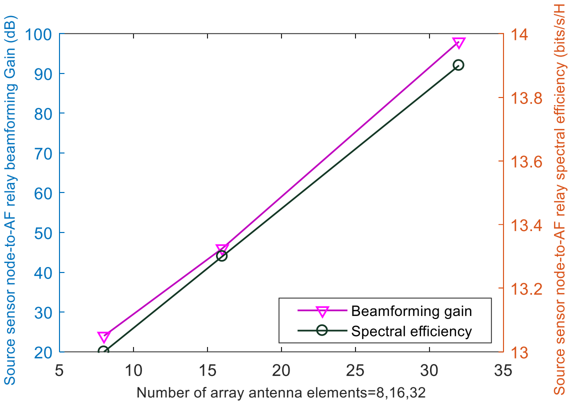

Figure 4. Source sensor node-to-AF relay beamforming gain G_{SR} and spectral efficiency against number of array antenna elements N_T, N_R = 8, 16 and 12 and RF chains N_{RF}^T =3 with link L=10 clusters and SNR=5dB.

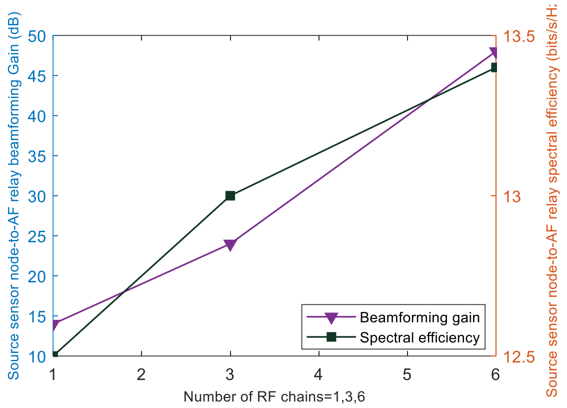

Figure 5. Source sensor node-to-AF relay beamforming gain G_{SR} and spectral efficiency against number of RF chains N_{RF}^T = 1, 3 and 6, number of array antenna elements N_T, N_R = 8 with link N=10 paths and SNR=5dB.

The beamforming gain G_{SR} produced is sufficient to overcome the additional propagation losses due to shadowing, rain and oxygen, which greatly affect mmWave propagation in outdoor environments. The results obtained by employing hybrid analog/digital beamforming could offset the additional propagation losses that usually occur in mmWave outdoor environments and guarantee a reliable mmWave link connection. The results obtained by employing hybrid beamforming is sufficient to offset the additional propagation losses in mmWave outdoor environments and extend the mmWave link coverage, considering the measured results in [34], where path loss measurements in mmWave outdoor environment at 60 GHz were carried out and revealed path loss of 110.2 dB for an aerial link (rooftop-to-rooftop) at a 98 meters travel distance and path loss of 117.05 dB for a ground link (light pole-to-light pole) at a 147 meters travel distance using 36 × 8 phased array antennas.

The results showed that signal transmission in mmWave outdoor environment through AF relay can be of great significance for mmWave WSNs for remote temperature monitoring applications in outdoor environments and can greatly help to compensate for the mmWave propagation losses due to blockages in mmWave outdoor environment. The proposed two-split optimum beamforming in mmWave WSN for remote temperature monitoring applications in outdoor environments utilizing hybrid analog and digital beamforming with multiple RF chains at the source sensor node and utilizing analog beamforming with a single RF chain at the AF relay improves the directivity/beamforming gain. The proposed two-split optimum beamforming strategy can help in overcoming the path losses that usually exist in mmWave outdoor environments by directing mmWave signal in order to obtain higher directivity and beamforming gain.

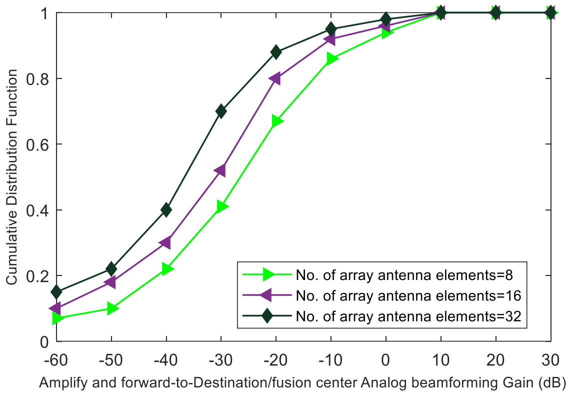

Figure 6. AF relay-to-Destination/fusion center beamforming gain G_{RD} cumulative distribution function with RF chain N_{RF}^{T} = 1, number of array antenna elementsN_R^T, N_D= 8, 16 and 32 with channel N=1 single path and SNR=5dB.

Research conducted by [8] measured atmospheric loss in mmWave outdoor settings caused by factors like rain and oxygen absorption, resulting in an attenuation of 18 dB/km. The enhancement of directivity and beamforming gain was observed in Fig. 6 when more array antenna elements were used in analog beamforming for the relay-to-destination/fusion center in the system. This improvement in performance can help mitigate the extra propagation losses that occur in outdoor mmWave environments.

The analysis of the end-to-end delay in transmission was also examined against the source sensor node to destination distance as shown in Fig. 7. The analysis revealed that unoptimized beamforming outperformed the optimized beamforming though this comes at a high cost of RF chains to match the increasing number of antenna elements. Multiple AF relays that are associated with the proper algorithms for routing can effectively combat the severe delay resulting from random blockages. For scenarios involving very narrow beams, it is much better to adopt direct transmission for a lower delay. Also, reflections may contribute heavily to the delay, but when properly used, they are viable for preserving the mmWave link connectivity.

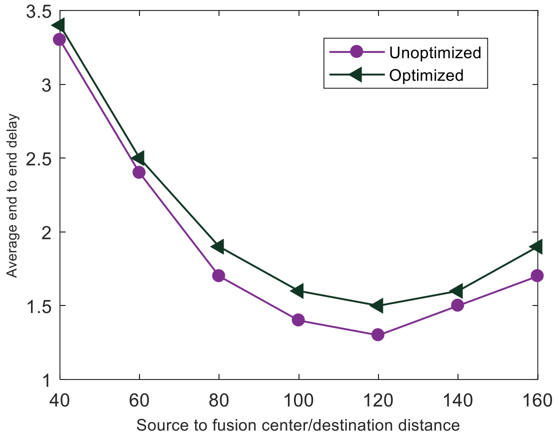

Figure 7. Average end to end delay with source to fusion center/destination distance. Number of RF chains N_{RF}^{T} = 1, N_{RF}^{T} =8 number of array antenna elementsN_R^T, N_D= 8, channel N=1 single path and SNR=5dB.

C. Comparison with Similar Studies

In this section, the numerical results of this study are compared with some of the previous studies of beamforming in mmWave outdoor environments as shown in Table II. Due to the inherent differences in the simulation methodology, some parameters may not be directly comparable. However, the impact of beamforming in the mm Wave WSN environments can be observed from the similarities and contrasts in the different studies.

TABLE II. Comparison of Beamforming Studies in MmWave Outdoor Environments

Source	mmWave Frequency (GHz)	Tx-Rx Distance (m)	Beamforming Strategy	Path Loss	Beamforming Gain	Array Size
W. Keusgen *et al.* [6]	60	-	-	18 dB/Km (Atmospheric loss)	-	-
B. P. Murray *et al.* [32]	60	98 147	- -	110.2 dB (Aerial link) 117.05 dB (Ground link)	- -	36×8
S. Hur *et al.* [30]		-	Adaptive subspace sampling and hierarchical beam codebooks	10dB wind sway misalignment degradation	30 dB	32
Our study	60	160	Two-split mix between Hybrid analog/digital beamforming and Analog beamforming	-	24 dB, 46 dB, 98 dB (Hybrid analog/digital beamforming with RF chains=3) 14 dB, 24dB, 48 dB (Hybrid analog/digital beamforming with RF chains=1, 3 and 6) 30 dB (Analog beamforming with RF chains=1)	8, 16 and 32 8 8

From the comparison of previous studies with this study, it can be seen that little research has been done for beamforming in outdoor environments, and indoor environment beamforming techniques do not easily extend to the outdoor environment since mmWaves are highly affected by propagation losses and blockages in the outdoor environment due to rain, oxygen and obstacles. Most of the research works focused on the significance of beamforming techniques in mmWave communication but do not mention what categories are suitable for deployment in outdoor environment WSNs for remote monitoring applications. Hence, this study investigated and identified beamforming techniques that can be employed for 60 GHz transmission in mmWave WSN for remote temperature monitoring and developed an optimum beamforming strategy using a two-split mix between hybrid analog/digital and analog beamforming strategies in an attempt to offset the additional propagation losses that exist in outdoor environments. The beamforming gain produced is sufficient to overcome the propagation losses. Relay-assisted transmission was also incorporated to avoid the blockages in the mmWave outdoor environment and extend the mmWave link connectivity.

V. CONCLUSION

In existing literature, research has shown that deploying mmWave WSNs for remote monitoring in outdoor environments still remains challenging. This work identified various beamforming techniques that are used in communication networks but there exists a research gap in optimum beamforming technique suitable in mmWave WSN for remote temperature monitoring applications in the outdoor environment. Therefore, this paper developed an optimum beamforming strategy for remote temperature monitoring in outdoor environments at the unlicensed 60 GHz mmWave frequency through a two-split mix between analog beamforming and hybrid analog/digital beamforming. Also, signal transmission and reception through AF relay-assisted mmWave is proposed for compensation of the signal fading effect as a result of strong shadowing and propagation losses. This will ensure great reliability in mmWave WSN communication. The study concluded that the employment of the developed two-split beamforming model in a relay assisted mmWave WSN for remote temperature monitoring in outdoor environment could significantly improve the efficiency and ultimately provide a much more reliable connection.

One of the major challenges in designing mmWave WSN systems for remote monitoring applications in the outdoor environment is the sensitivity to blockages in the outdoor environment. Research in mmWave communication will require incorporating sensitivity to the blockages in the outdoor environment and even more complex outdoor mmWave channel models to aid in the analysis. In order to effectively apply mmWave techniques to WSNs for remote temperature monitoring applications in outdoor environments while guaranteeing effective mmWave link connectivity, effective anti-blockage techniques are needed by which the mmWave WSN system can be able to perform adaptive switching from a LOS transmission mode to a NLOS transmission mode in order to maintain seamless WSN connectivity. An extension of the work in this research study is its implementation in the practical field and adopting the proposed model in real-life outdoor environment scenarios. Taking the blockage effect into consideration, a possible extension of the work in this research study is adaptive relay-assisted mmWave WSNs for remote temperature monitoring in the outdoor environment. Finally, blockages in the mmWave WSNs for remote temperature monitoring in the outdoor environment are usually due to concrete buildings, light posts, and trees that are impenetrable by mmWaves. This may be avoided to a greater extent by employing multiple relays in the mmWave WSN. An interesting extension of this work is therefore investigating the impact of blockage in multiple relay-assisted mmWave WSN for remote temperature monitoring in the outdoor environment, investigating the active relays' distribution considering the blockage effect, and developing a model capable of selecting the best relay in order to avoid the blockage in the mmWave WSN outdoor environment.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors carried out the conceptualization. The development methodology was done by Ogwal, Joseph and Ebenezer. Ogwal and Ebenezer did the software simulation, while validation was done by Joseph, Ebenezer, Joseph, and Edwin. Ogwal, Joseph and Ebenezer initiated the formal analysis. Ogwal, Joseph and Ebenezer prepared the original draft, while Joseph and Edwin reviewed and edited it. Supervision was under Joseph and Ebenezer. Edwin carried out project administration and funding for the APC was done by Ebenezer and Edwin. All authors had approved the final version.

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