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Modelling of Quantum Based Cloud Radio Access Networks

A Thesis Submitted to the Institute of Laser for Postgraduate Studies, University of Baghdad in Partial Fulfillment of the Requirements for the Degree of Master of Science in Laser/Electronic and Communication Engineering

By

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To my beloved family and friends.

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SYMBOLS

θ	quBit state
α	Probability amplitudes of the photon to be 0
β	Probability amplitudes of the photon to be 1
λ	Hermitian operator
a_n	Photon state
σ	Entangled photon state
Q_{ee}	Quantum energy efficiency
P_{server}	Power consumption of the BBU server
$P^t_{n,u}$	Power transmitted from RRH n to UE u
$h_{m,u}$	Channel gain from n-th RRH to u-th UE
$r_{n,u}$	Path loss between RRH n and UE u
α	Path loss exponent
$d_{n,u}$	Straight line distance between n-th RRH and u-th UE
$p_{i,n,u}$	Power of photon i from RRH n to UE u
$A_{i,n,u}$	Attenuation of photon i from RRH n to UE u
P_{cloud}	Cloud network power consumption
$P_{enanglement}$	Power consumption of quantum entanglement
P_{laser}	Laser power consumption

$P_{detector}$	Detector Power consumption
L	The number of Lasers
D	The number of detectors
N	Total number of active RRHs
σ_{DC}	DC-DC loss factor
σ_{AC}	AC-DC loss factor
σ_{cool}	Cooling loss factor
P_{QC}	Total PC of quantum cloud
P_{RRH}	Power consumption of the RRH RRH
P_{PA}	Power consumption of PA
η_{PA}	PA efficiency
$\tau_{n,o}$	link delay from RRH to the pool
c	Speed of light
ind	Refractive index
τ_{BBU}	Execution time of the BBU processing
τ^{int}	Initial device delay
$\tau_{n,u}$	Delay from the UE to the RRH
mod	Constant factor of resource blocks increment
$\tau_{traditional}$	Total delay of traditional network
τ_{Q}	Total delay of quantum case
τ_{laser}	Time delays of the laser
$\tau_{detector}$	Time delays of detector
τ_{Δ}	Delay gain
$\uplus$	Number of entangled photon pairs
P_{Δ}	Power consumed by X2AP protocol

ABBREVIATIONS

BBU	base band unit
CAPEX	capital expenditure
CA	carrier aggregation
CN	core network
CPU	central processing unit
C-RAN	cloud radio access network
CoMP	Coordinated multi point
eNodeB	evolved NodeB
EPC	evolved packet core
EPS	evolved packet system
E-UTRAN	evolved universal tele. radio access network
GSM	global system for mobile communications
H-CRAN	Heterogeneous C-RAN
HetNet	heterogeneous network
HSPA	high speed packet access
HSS	home subscriber server
HV	hypervisor
LTE-A	LTE Advanced

LTE	long term evolution
MME	mobility management entity
MIMO	Multiple-input multiple-output
mmWave	millimeter wave
NFV	network function virtualisation
OFDMA	orthogonal frequency division multiple access
OPEX	operational expenditure
PCRF	policy and charging rules function
PGW	packet gateway
QoS	quality of service
RF	radio frequency
RRH	remote radio head
SAE	system architecture evolution
SC-FDM	single carrier-frequency domain multiplexing
SDN	software defined network
S	number of BBU servers
SE	spectral efficiency
SGW	serving gateway
SNR	signal-to-noise ratio
UE	user equipment
UMTS	universal mobile telecommunication system
VM	virtual machine
3GPP	third mobile generation partnership project
4G	fourth generation
5G	fifth generation

Abstract

Quantum computing gives an answer for some issues that classical networks experience, yet the information hole between these two isn't crossed over yet. In like manner, this thesis has proposed assessments and modern quantum answers for the cloud based mobile communications. This proposal shows the impact of utilizing quantum entanglement to diminish the signalling delay cost that the conventional cloud faces. Through demonstrating and modelling the two systems, i.e. traditional cloud and quantum based cloud, this work guarantees a delay decrement by at least 10%. To do this, demonstrating the power utilization/consumption (PC) and energy efficiency of conventional and quantum based cloud systems is essential. This work additionally shows, by means of demonstrating the PC, that introducing a quantum based paradigm isn't power consuming strategy, rather, it shows indistinguishable power and energy efficiency figures with a chance of progress.

Chapter 1: Introduction and Literature Survey

1.1 Overview

Based on Ericson and Cisco recent reports, mobile devices and connections can grow to 11.5 billion by 2020, which symbolises ten-fold increment in the mobile networks data traffic between the years 2013 and 2020 [1], [2]. Reportedly, Ericsson stated that by 2021, the number of 5G connected devices can reach up to 150 billions, rising from 4.1 billion device connections in 2013 regarding using long term evolution (LTE) technology [3]. This is because the new technologies and evolved applications have urged the users to use more devices, including mobile phones, tablets, lap tops, etc. In addition, with offered high data rates, innovative devices are required, not to mention the increased number of world populations. To serve such increment, it is required to innovate new technologies that can help boosting the networks to their maximum efficiency. It is worth mentioning that LTE, called 3GPP or Release 8, represents the newest version of the third generation partnership project (3GPP).

This release is issued to cover the shortcoming of older generations, such as global system for mobile communications (GSM), universal mobile telecommunication system (UMTS), high speed packet access (HSPA), etc. These systems compete for at least 10 years before LTE emerges. LTE system is launched to compete for at least 10 coming years. The main objectives of this system were [4]:

- Reduced latency.
- Packet based communication network architecture.
- Flexible frequency bands between 1.25-20 MHz.
- Higher data rates, up to 100 Mbps in downlink, and about 50 Mbps in uplink transmission.

Before discussing the LTE architecture, it is worth showing the evolution of different communication generations, as in Figure 1.1 [5].

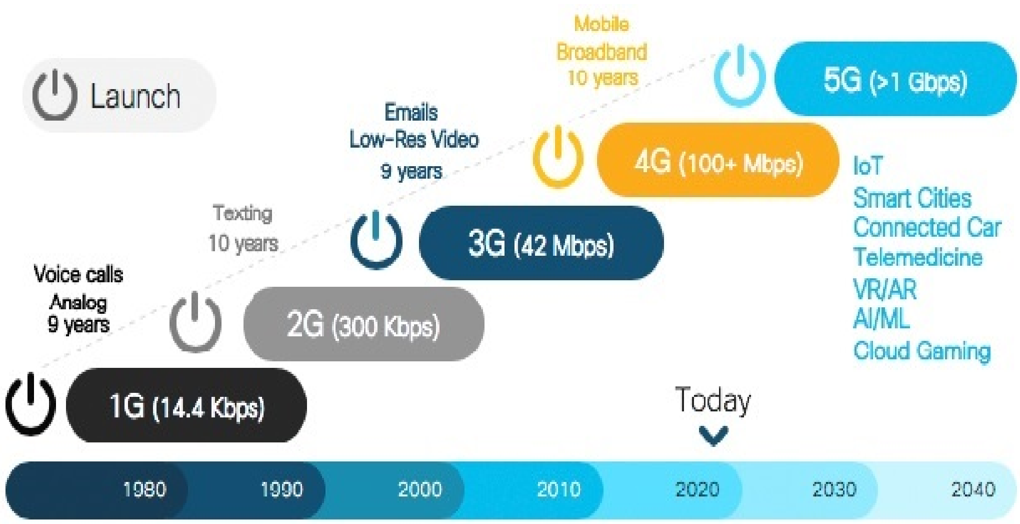

Fig. 1.1.: Evolution of communications generations towards 5G [5].

1.2 LTE Architecture

In LTE, upgrading the legacy UMTS system yielded the evolved universal telecommunication radio access network (E-UTRAN), the latter and system architecture evolution (SAE) which contains the evolved packet core (EPC), they resulted evolved packet system (EPS) [6]. Packet based system indicates that the information is sub-divided into what is called packets. These packets are sent through the network/circuit to the host. In this system, an individual packet can take variant route within the network via using different algorithms that rout each packet to the final destination. This idea/logic contrasts the circuit switching based systems where there is is a static rout that is pre-established before the connection initialization [6].

Essentially, LTE architecture is consisted of three major parts, EPC, E-UTRAN and the users (UEs), as shown in Figure 1.2. E-UTRAN contains of several eNodeBs, which is responsible of offering the necessary air interface for the UEs, receiving and precessing the data, and providing the proper resources scheduling that achieves the maximum network performance. When a call is required to be established, the data plane of the UEs that are handled by using (S1-U) interface is directed to the serving gate way (SGW) from the eNodeB, from the SGW, the data will be directed to the target eNodeB and the target UE [7]. Meanwhile, the mobility management entity (MME) will be updated by this step from the source eNodeB while using (S1-MME), that is responsible for interfacing the control plane. The UE's position will be updated at the SGW by the MME for necessary future services and other mobility functions. Subsequently, the SGW is responsible for routing and routing the UEs' packets for their final destination. When the UE establishes a call to other network or to when connects to the Internet, in this case the the packets will be forwardedto the packet gate way (PGW) by the SGW. Finally, the PGW can achieve several functions, such as charging in case of inter-operators calls, packets filtering, allocation the required IPs to the UEs [8].

1.2.1 User Equipment (UE)

The UE term can be understood as computer, mobile device, tablets, laptops, or any connected device. This device is the only object that the costumer can explore, and other network parts are hidden from the UEs and run by the service operator. It is worth mentioning that this object is the least part of the network that is taken care of when thinking about reducing the power consumption or reducing the overall signalling the UE encounters when applying new technologies such as device to device services [9]. In the latter, the UE can be used as a gate to route the connection between two UEs. Such ignorance is originated from the fact that this caring will not benefit the network operators. In addition, the UE can easily charge his device with necessary power as required [10].

1.2.2 Evolved Universal Telecommunication Radio Access Network (E-UTRAN)

Second part of the network consists of several evolved NodeBs, called eNodeBs, these are communicated and connected amongst each others via X2-interface for necessary handover operations, while S1 interface is used to connect these eNodeBs to the EPC. The eNodeB therefore bridge and connect the UEs to the core network (CN), further to providing the necessary data and control protocols. In addition, the eNodeBs are responsible for:

1. Allocating the available resources to the connected users.
2. Scheduling the available resources amongst different UEs in frequency and time dimensions [11]. This is done with assuring the target quality of service (QoS) to the UEs.
3. Moreover, the eNodeBs are responsible for mobility management functions, such as radio link measurement and handover signalling.

It is worth mentioning that this part of the network is the most vital part as it is directly in touch with the UEs for providing good services and updating. It is also the main part where most of the power is consumed and the number of available resource blocks are scheduled efficiently. Hence, the network providers are aiming to find new solution that help reducing the eNodeBs complexity [12].

1.2.3 Evolved packet core (EPC)

Also called core network (CN), EPC contains three main parts: PGW, SGW and MME. In addition, the CN is responsible for administrating some logical entities, such as charging and policy function (PCRF) and home subscriber server (HSS). Each part is further responsible for several functions: the MME is in charge of inter-CN handover and mobility signalling and handover with networks other than 3GPP, authorization, authentication, bearer management and time zone signalling function, which involves bearers deactivation/activation procedures. The EPS bearer can be defined as the way the traffic of the UE will be dealt with when passing via the network [4].

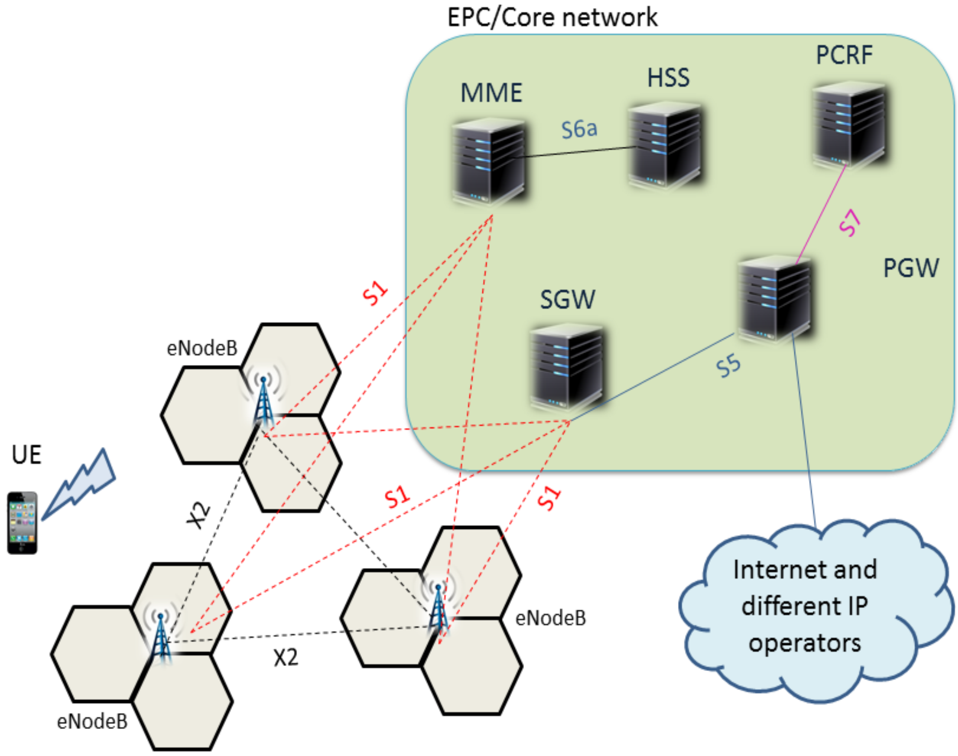

Fig. 1.2.: LTE E-UTRAN architecture [13]. It presents three main sections of LTE: EPC, E-UTRAN and UE. E-UTRAN with many eNodeBs, EPC contains PGW, SGW, PCRF, HSS and MME units.

1.3 LTE-A Techniques

There are several techniques that are proposed to embrace LTE system further more to an advanced one, which is LTE-Advanced (LTE-A) or (3GPP Release 10). These techniques, innovations and paradigms were used in LTE system to achieve higher capacity, further coverage, lower latency and maximum throughput (net capacity or net data rate after excluding the bits error rate), which results in near optimum UE QoS and satisfaction [4]. Moreover, LTE-A is capable of supporting heterogeneous oriented networks, where low power cells such as relays, Femto, Pico and cells are located within the higher power Macro cells. However, LTE-A techniques can be briefly summarised, as follows:

1. Carrier aggregation (CA)

   This method is used to achieve around 1 Gbps maximum rate. This technique combines disparate or several spectrum band to produce a wider band that can serve an individual UE [14]. For instance, a service provider (SP) has 10 MHz bandwidth in 800 MHz and 20 MHz in 1900 MHz spectrum, it is now possible to gather both bandwidths to yield 30 MHz. This number can grow to an upper limit, which is 100 MHz.

2. Multiple-input multiple-output (MIMO)

   Multiple-input multiple-output (MIMO) refers to the communication systems where both the transmitter and the receiver operate using multiple antennas. MIMO technology represents one of the key factors that helped to embrace LTE. First the MIMO number of antennas was maximised to four. Now on, this number continues to grow in regards to LTE-A. The latter requires that to achieve the maximum spectral efficiency, it was needed to used 8×8 antennas multiplexing. Note that spectral efficiency means how many bit/s to be transmitted in one Hz (bit/s/Hz). Apposite to LTE, for a single UE, uplink MIMO is utilised in LTE-A with four layers [15].

3. Coordinated multi point (CoMP)

   Coordinated multi point (CoMP) or what is called (3GPP, Release 11) is also a key improving factor for LTE-A, it aimed at effectively maximising the average data rate or capacity of the coverage cells, increase the signal-to-noise ratio (SNR), and provides an optimised usage for the system resources [16]. CoMP enables the communications amongst several eNodeBs to avoid the interference signals of the whole network dynamically. Therefore, the downlink transmission becomes more efficient and dramatically enhanced. The idea of CoMP includes that all signals transmitted by the coordinated eNodeBs assist to cancel the mutual interference [16]. Since the same bandwidth is in use by all eNodeBs' sectors, this leads towards increasing the interference at the UEs who are in the cell edge in case that signals are received at the same time from multiple eNodeBs.

4. Relay nodes and Heterogeneous networks (HetNet)

   Relays are nodes that are distributed at the edges of the cells for expanding the coverage and providing better capacity. Such low power spots act as repeaters, their purpose rebroadcasting the received or transmitted signals to enhance the quality of the signals [17].

   Relays are capable of connecting to eNodeBs using wireless links. Such paradigm provides an important savings regarding the deployment cost if compared to the case of deploying bare new eNodeBs. This concept also ties to the concept of HetNet. Towards increasing the capacity and coverage of the network, HetNets are capable of combining different sizes of transmitting nodes, each with different output power and access technology to cooperate in the cell site or the area of coverage. The small coverage cells are distributed within the large cells to serve large number of devices or UEs in synchronously, which improves the QoS [18].

Apart of the previously mentioned technologies, some other evolutionary methods are also suggested within LTE-A, for example, self-organizing networks that aim to automate the CN by using advanced and intelligent algorithms to make configuration, healing, planning, managing and optimizing the mobile networks faster and simpler. Another interesting technology is called cognitive radio, this method aim to borrow some bandwidth slots, called white bandwidth, from technologies other than mobile networks and utilise them into proving more available spectrum and therefore, higher capacity. For example, borrowing the non utilised TV or radio spectrum in the area of interest for some time to serve the UEs with high data rates requirements [19].

1.4 Beyond 4G

Mobile operators constantly seek out new and innovative, designs, ideas, protocols and more advanced digital signal processing (DSP) methods to efficiently stand uo to the excessive demand for traffic, at the same time, providing faster and scalable connectivity to the UEs [20].

The 5G communication systems are required to achieve around 1000 times capacity more than today, reduce the consumed energy for each service by 90 %, offer extra spectral capacity, about 1 Tera bits/s per km^2 to facilitate the dense networks, 10 times additional battery life and connected devices. In addition, the 5G system are required to achieve reduced latency, about 5 times less when compared to the current 4G generation [21], [22]. It is worth mentioning that most futuristic algorithms rely upon over-provisioning the available resources to ensure that the typical data demands are met, for example, applying spectral aggregation and spatial densification by deploying higher number of cells [23]. However, these types of solutions are power consuming processes, thus, the network cost is increased which is not a satisfactory issue for the network operators. To overcome such limitation, new designs and network paradigms are a must [24] to fullfil the next generation requirements, as shown in Figure 1.3 [25].

The emerging technologies that offers these requirements can be variant regarding their general purpose, below, some of the key technologies that are suggested for 5G networks are briefly presented [26]:

1. Cloud radio access network (C-RAN)

   C-RAN architecture is newly suggested by many operators such as France -Telecom/Orange, Telefonica, KT, NTT, SoftBank/Sprint, and China Mobile. In addition, it was embraced by equipment vendors, such as Liquid Radio, Alcatel-Lucent, Nokia, Siemens, and Light Radio.

   C-RAN is displayed as a prerequisite and a must technology to achieve 5G networks with higher performance [27]. This architecture is presented as an updated version for the existing traditional

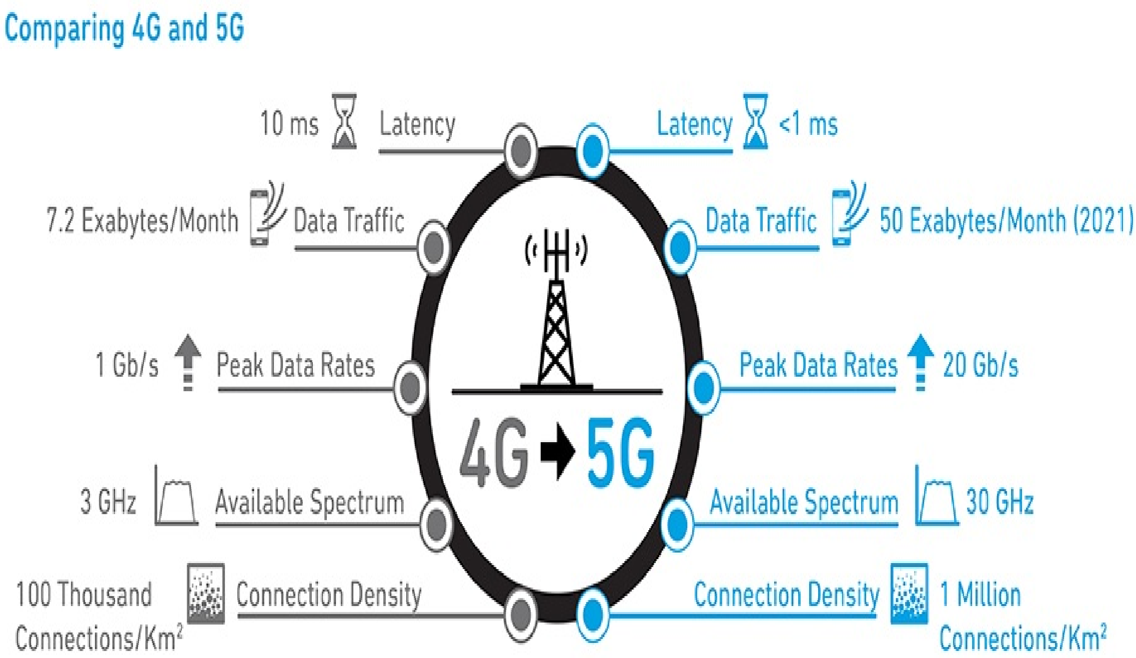

Fig. 1.3.: Comparison of 4G and 5G requirements [25].

based networks, that inherits the cloud computing concept into mobile systems [28], [29]. In C-RAN, there are many remote radio head (RRH) units and base band units (BBUs) that are combined and cooperated in one place, called base band unit BBU pool, as they are shown in Figure 1.4. The RRHs are operated with low power and therefore distributed and replaced the traditional eNodeBs, and connected to the BBUs and the BBU pool by either optical fibers with high-bandwidth, or via wireless links [30], [10]. The BBU pool is also called cloud or data center, which hosts large number of BBUs. Such deployment of C-RAN will ensure reducing the operational (OPEX) cost, and the capital (CAPEX) cost too. This is because the site visits will be reduced, the total maintenance and building leases will be mitigated, which finally decreases the total required cost of operation [31]. In addition, such paradigm permits dynamic resources allocations amongst all RRHs and BBUs, enables an advanced offloading techniques to facilitate sharing processing the UEs' load via any BBUs within the pool. In this case, some energy can be saved due to switching-off the unused BBUs. This cooperation enhances the network's capacity and throughput, and boosts energy and spectral efficiencies [32].

Moreover, the required cooling will be reducible as cooling each site demands substantial cooling cost. In C-RAN, there are many pools that are distributed within an enlarged geographical area. At each pool, few cooling units are required for the gathered BBUs, when compared to the traditional sites, each BBU demands an individual cooling unit.

2. Heterogeneous C-RAN (H-CRAN)

   H-CRAN paradigm makes use of both traditional HetNets and C-RANs.

   H-CRAN architecture aims integration between the existing high power Macro BSs deployment with low power RRHs to produce what is called Heterogeneous based Cloud Radio Access Networks (H-CRAN). In this paradigm, the Macro BSs cooperate and coexist with C-RAN [10]. This cooperation allows the low power RRHs to be collaborated together in the pool, while the Macro stations interface

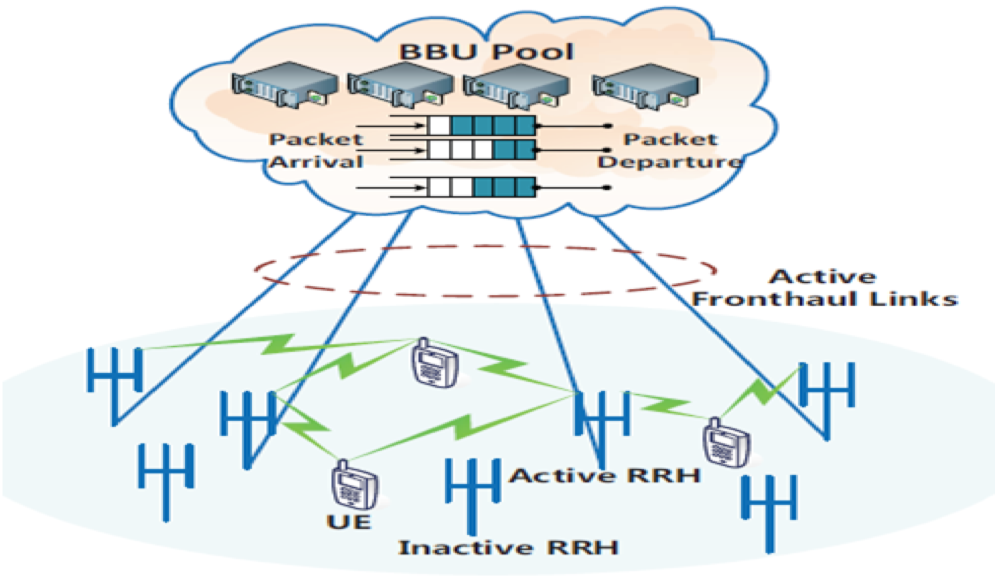

Fig. 1.4.: C-RAN network architecture [30].

the pool by using X2 and S1 protocol stacks to allow control and data plane connectivity, respectively.

H-CRAN aims to deliver co-operational service in dense areas. It makes advantages of the RRHs that provide higher data rates to the UE, concurrent with guaranteed QoS. Alongside, H-CRANs secure the coverage to UEs that demand lower QoS requirements via Marco BSs [18]. The RRHs cooperate together in the BBU pool to revoke the signalling with Macro base station, at the same time, the BBU pool is connected with Macro BS for necessary inter tier interference coordination [10]. In this case, the challenges that are facing traditional HetNets will be mitigated. In traditional HetNets, a huge signalling process is required to coordinate the process of transmission and reception, the inter-tier interference and handover process amongst small coverage cells such as Pico and Femto with high power Marco stations, as shown in Figure 1.5.

In addition, the densely distributed small coverage cells can improve the UE's capacity, however, this comes with enlarged energy consumption, and this can degrade the energy efficiency performance.

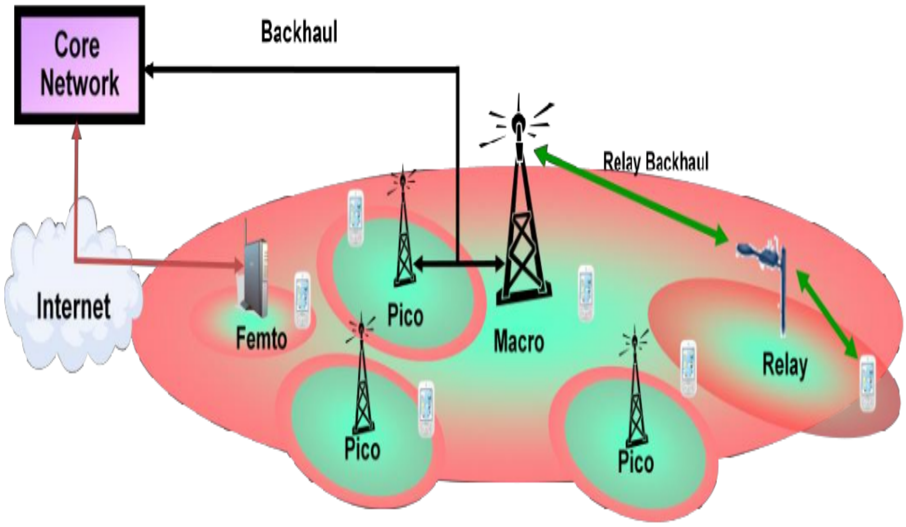

Fig. 1.5.: Heterogeneous network architecture [10].

3. Software defined network (SDN)

SDNs are leading technology towards modifying how the network's control plane can be managed to provide an enhanced communication strategy [27]. Conventionally, any device within the network includes data palne as well as control plane that are facilitated using protocols or functions. SDN in turn aims separating the functions of control plane from the device, then place these functions (of all network devices) in centralized servers, called controllers [33].

as shown in Figure 1.6.

This idea enables functioning the network's control plane using bare software to mitigate the increased complexity of network devices. Subsequently, replacing these forwarding devices with open-flow switches with much less intelligent [34]. The controller is responsible of installing and updating any flow forwarding rules and processing instructions within the forwarding devices, along with gathering the network status.

SDN implementation will offer a general view to the networks, it will help manipulating and reducing the network resources dynamically, innovating advanced and services and policies, and offering the required network administration.

Moreover, SDNs provide much smarter ways for the active network links, this also enhances the system throughput [35], reduces the network maintenance cost, and settle for low hardware cost [36]. Furthermore, SDN controllers are able to upgrade and update open flow switches intelligently, at the same time, connecting the legacy control plane unites of the mobile networks, such as PGW, SGW and the MME.

4. Network function virtualization (NFV)

   Another split within the network procedures is the separation of materialistic hardware and network functions that are set up at them, this means that the functions will be dispatched as plain software [9], [37].

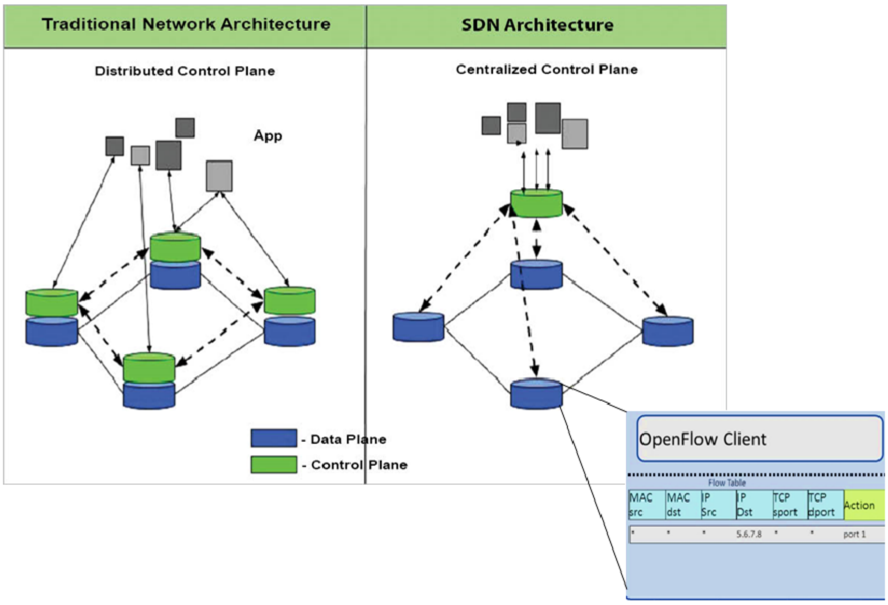

Fig. 1.6.: Comparison between SDN and traditional network architecture [34].

Basically virualizing means that the network functions will be implemented using software, called virtual machines (VMs), rather than using an individual hardware for each function. These software can be installed in one of the hardware and controlled by VM supervisor/hypervisor that manages which VM can use the hardware resources at what time slot without reducing the network efficiency [38]. At this point, running a small number of virtualized BBU servers to operate the network becomes conceivable while achieving the required QoS for the UEs [21], [39]. Recently, using NFV in the cloud centres has been embraced by the academic community for many reasons, such as it helps allocating the network resources flexibly, operating and configuring the virtualised servers becomes flexible, total cost of maintenance and cooling is reduced, multi tenancy procedure will be easy and available, on top of these, the energy consumption will be easily reduced.

Therefore, virtualising the network has been chosen to achieve magnificent rising in the energy efficiency, this permits the service providers to perform the network functions by using only software instead of using a proprietary built-in and dedicated equipment. As for the latter, updating, upgrading and expressing advanced and new applications and services to enable 5G paradigm shift is considerably intractable.

NFV also embraces and enables using the common off-the-shelf BBU servers for running the functions' software. Figure 1.7 presents the idea of virtualisation as several VMs share a virtualised server resources.

5. Millimeter Wave (mmWave) technology for next generation

   The communication networks are usually limited to a very narrow bands of frequencies when they operate, this range can be found about few to hundreds of MHz, up to few GHz. A for nowadays, this available band is mostly fully occupied when there is a peak time period regardless how optimised and efficient are the algorithms and scheduling techniques that are used to allocate the available resources. However, more bandwidth is urgently required [40]. A spectrum range amongst 30–300 GHz is fortunately available, called

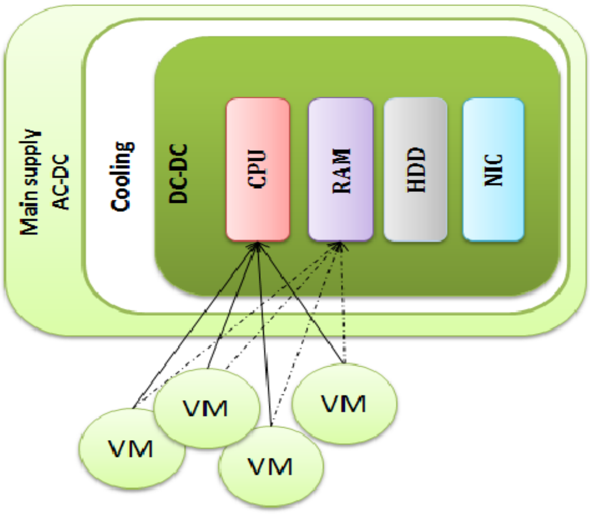

Fig. 1.7.: The concept of virtualisation, several VMs sharing the server resources.

mmWave, can basically offer a large amount of frequency sub-bands, that can be used in mobile networks transmission.

Nevertheless, it was deemed difficult and intractable to implement these offered bands until recently, this comes with different reasons: the large path degrades its propagation quality, it is more susceptible to the atmospheric and rain absorption, it has no diffraction, neither penetration ability when facing the objects or high building, which makes application such techniques is constrained to a short range based transmission. However, if these bands are used radio over fiber technologies, they seem promising than wireless link transmission. The radio over fiber technology requires the light to be modulated by using radio signal, after that, the modulated signal travels using optical fiber to the receiver where the original wireless signal is extracted. In this procedure, the higher bandwidth can be provided. In addition, low cost technology becomes available [41]. Furthermore, the design of the base stations can be simplified [42].

It was worth mentioning that mobile communication networks alone consume 0.5% of the global energy consumption [43]. Part of this power is consumed in the signalling process and control plane as more network subscribers means growing in this cost due to providing extended interfaces and protocols. Consequently, a re-design for the existing network paradigm and offering new innovative solutions can help overcoming some of these inefficiencies [44].

As for traditional/classical communication, enhancing the network matrices run to a limit. For example, the size of manufactured transistors is now very limited, and no futuristic reduction can be achieved in Moore's law. As such, every 2 years, the number of manufactured transistor doubles in a circuit, ultimately, this law reaches its limit too. In addition, the resources allocating techniques of the available bandwidth are no longer able to enhance the spectral efficiency due to an inherently limited number resource blocks [45]. Likewise, processing delay and power consumption of a device has a limit to reach. Hence, the limitations of classical communications has to be overcome by using far more effective technology, that is, utilising quantum mechanics in classical communications, which represents a reliable and incredible method to achieve the requirements of the beyond existed generation, as will be explained in the coming Chapter.

1.5 Quantum Preliminaries

Mathematically, a quBit (θ) is denoted as $|\theta\rangle = \alpha|0\rangle + \beta|1\rangle$ or $|\theta\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$, [78], where α and β are the probability amplitudes of the photon to be 0 or 1, respectively. This phenomenon is called a superposition. Through the possibilities α and β, it is not accessible to know if the quBit is holding the state $|0\rangle$ or $|1\rangle$ [78]. Any two states system can encode the quBit, such as nuclei's spin, electrons' spin, and photons' polarization. Nevertheless, photons are idealistic to serve as quBits due to their low interaction with other photons which achieves low de-coherence, this means the quBit maintains its states for very long time, as well as travelling at speed of light. However, up on measuring the quBit, it collapses to one of its bases/states, i.e. either $|0\rangle$ or $|1\rangle$, the obtained basis is now specified by the complex number's absolute value. Hence, the state $|0\rangle$ is specified with the probability $|\alpha|^2$, and the state $|1\rangle$ is specified by $|\beta|^2$, as the sum of probabilities is $|\alpha|^2+|\beta|^2 = 1$ [79]. To elaborate about how the photon is dealt with and how the polarization of its states can be identified and mathematically represented, some examples are explained. The photon can be represented with probability amplitudes:

$$|\theta\rangle = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \tag{1.1}$$

where the quBit can be written as $|\theta\rangle = \alpha|a_1\rangle + \beta|a_2\rangle$, as $|a_1\rangle$ and $|a_2\rangle$ are the states of a single photon, which can be horisontal or vertical polarization.

If a photon is passing a horizontal polariser, the probability amplitudes of this case can be represented as:

$$|-\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{1.2}$$

which is also can be written as $1|a_1\rangle + 0|a_2\rangle$ where the first state (horizontal, $|a_1\rangle = |-\rangle$) has the probability of 1, and the probability of the second state (vertical, $|a_2\rangle = ||\rangle$) is 0, Subsequently, the vertical polarization case can be represented by [80]:

$$||\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{1.3}$$

Similarly to the above elaboration, this case can be written as $0|a_1\rangle + 1|a_2\rangle$ as the probability of the second state is 1, while the first state is 0. The other state that can be produced is when the vertical or horizontal light passes through a +45 degree polariser, this state can be represented as $|/\rangle = \frac{1}{\sqrt{2}}|a_1\rangle + \frac{1}{\sqrt{2}}|a_2\rangle$. The probability amplitude of this case is given as

$$|/\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} \tag{1.4}$$

which means the probability of the photon being horizontal is $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$, and the probability of being vertical is also $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$. In case of -45 photon polarization state is equivalent to $|\backslash\rangle = \frac{1}{\sqrt{2}}|a_1\rangle - \frac{1}{\sqrt{2}}|a_2\rangle$. The probability amplitude of this case is given as [81]:

$$|\backslash\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix} \tag{1.5}$$

which means the probability of the photon being horizontal is $(\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$, and the probability of being vertical is also $(-\frac{1}{\sqrt{2}})^2 = \frac{1}{2}$. However, in the last two cases, the photon passes the 45/-45 polariser will have less intensity than the coming, it will be $cos^2(45)$ or $cos^2(-45)$, respectively [82]. If we apply Hermitian operator up on these two cases, it will produce eigenvalues $\lambda = 1$ and $\lambda = -1$ for the two states $|/\rangle$ and $|\backslash\rangle$, respectively. Here, we simply explain what is the meaning of eigenvalue, eigenvector or Hermitian operator. If a device, for example, a vertical polariser with two light indicators green and red on the side of the polariser. When the light goes through this device, if it is vertically polarised, the green light is on, otherwise the red light is on. This light represents the eigenvalue of the experiment because there is no way to know the state of the light without measuring it. Hence, the result of the measurement is called eigenvalue (λ_n) and will be either 1 or -1, while the state of the coming photon is called eigenvector, and the polariser device represents the Hermitian operator. It is worth noting that we cannot directly measure the state of the photon, rather we have to look at the result of the measurement, i.e. λ_n, that is the Hermitian of a state (a_n).

$$H|a_n\rangle = \lambda_n|a_n\rangle \tag{1.6}$$

we will simplify this formula by giving an example when a measurement is performed on a specific state, presumably, state of horizontal polarization of a photon. The Hermitian matrix (H) can be given as [83]:

$$H = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \tag{1.7}$$

when applying formula (1.6) on the ($-$) state, i.e. $H|-\rangle = \lambda|-\rangle$, it produces

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = +1 \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{1.8}$$

Here we notice that the two arrays that represents the horizontal states are identical for both sides of the equation, concurrent with an eigenvalue of ($\lambda = +1$), which means the coming horizontal light fully passes the horizontal polariser. On the other side, the Hermitian operator of vertical state, i.e. $H||\rangle = \lambda||\rangle$ as follows:

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = -1 \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{1.9}$$

it is clear that this case produces $\lambda = -1$, this simply means the coming vertical light will not pass through the horizontal polariser. Now what if the coming light is following an angle?. Generally, the photon will have an intensity of $cos^2(\theta)$, where θ is the polariser angle that has a probability amplitudes of horizontal and vertical polarization [84].

As explained earlier, the probability amplitude (α) represents the x coordinate, as shown in Fig. 1.8. Generally, it can be written as ($cos(\theta)$), while β represents y coordinate and written as $(sin(\theta))$ if the length of the vector is 1. This means if the photon is prepared with θ direction, the probability this photon is going through horizontal polariser is $|cos(\theta)|^2$ and the probability to go through vertical polariser is $|sin(\theta)|^2$ [85]. Accordingly, a photon with θ angle of polarization has its own orthogonal state, with probability amplitude $\alpha = -sin(\theta)$ and $\beta = cos(\theta)$ as shown in Figure 1.8, where the inner product of the orthogonal states is 0, as shown below where the product of 45 and -45 degree photon states produces 0, which applies to the entangled photons [63].

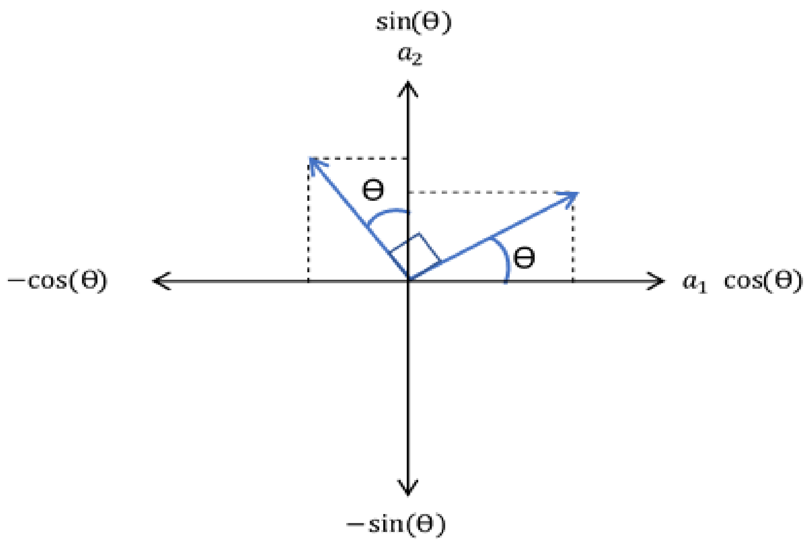

Fig. 1.8.: Representation of orthogonality of a two entangled photons.

$$\langle / | \backslash \rangle = \begin{pmatrix} cos(\theta) sin(\theta) \end{pmatrix} \begin{pmatrix} -sin(\theta) \\ cos(\theta) \end{pmatrix} = 0 \tag{1.10}$$

To generalise this, if a photon is polarised with α angle is going through β polariser. The quantum state probability amplitude is given as [63]

$$|\alpha\rangle = \begin{bmatrix} cos(\alpha) \\ sin(\alpha) \end{bmatrix} \tag{1.11}$$

and

$$|\beta\rangle = \begin{bmatrix} cos(\beta) \\ sin(\beta) \end{bmatrix} \tag{1.12}$$

Then, the probability of a photon prepared in α angle state to go through β angle polariser is given as:

$$|\langle\beta|\alpha\rangle|^2 = \left(\begin{pmatrix} cos(\beta) sin(\beta) \end{pmatrix} \begin{pmatrix} cos(\alpha) \\ sin(\alpha) \end{pmatrix} \right)^2 \tag{1.13}$$

$$|\langle\beta|\alpha\rangle|^2 = (cos(\alpha - \beta))^2 \tag{1.14}$$

If $\theta = \alpha - \beta$, then this probability returns $cos^2(\theta)$, as explained earlier.

1.6 Literature Survey

In [46], the cost of classical-quantum adaptation is described. The work in [47] has studied the quantum computing systems from technical point of view, including quantum gates, memory, CPU, error corrections and controlling. In [48], some properties, especially the correlation between classical and quantum quantum system has been studied. In addition, the capacity of some quantum channels is studied in [49].

More extensively, the channel capacities of quantum systems are studied in [50]. Moreover, quantum repeater was proposed in [51] to reduce the error probability that increases exponentially with respect to the length of quantum channel. In [52], a satellite is used to transfer entangled photons or single photon to provide long distance (100 km) solution for quantum networks using optical fiber or wireless links. This work advocates the validity of long distance, entanglement based classical networks. In addition, [53] proposed a model that provides an applicable solution using entanglement distribution method with high fidelity to be utilised in quantum Internet networks. Moreover, based on entanglement availability, the authors in [54] have proposed quantum based Internet scenario that is used when the network UEs have differentiated priority, or the amount of available entanglement pairs is limited. In [55], multilayer optimization technique has been proposed in quantum entanglement based Internet, this method minimizes the execution time of the quantum memory in the node, maximizes the throughput of the entanglement links, and reduces the number those links.

The security while using entanglement is discussed in [56] to permit secure key quBits distribution of instantaneous transmission of information. Another research used a free-space entangled photons distribution over 13 km of noisy atmosphere, was experimental reported in [57]. After such a distance, the experiment showed that entangled pairs can still be survived. The classical information was sent using quantum entanglement assisted channel between two parties, where the quantum, classical and power consumption rates while using coding schemes are all evaluated [58]. This work also proposed a protocol for such type of communications. In [59], entangled photon pairs are used to improve the capacity of the communication system through using the correlation behaviour to encode more number of bits, using optical fiber channel. Finally, the work in [60] have proved that both quantum and classical information are able to communicate without sharing a reference signal by using the correlation of entangled photon for such purpose.

However, there are several technologies, protocols and advances within the field of quantum based communications. In [61] and [62], they used optical fibre oriented quantum communications for Ground-ground and ground-space communication protocols. Subsequently, the authors of [63] used the non-cloning theorem for ciphering and security purposes. In [63], the non-cloning theorem has been used for ciphering and security. The quantum key distribution is used for quantum channel security in [64]. In addition, the authors of [65] have used the quantum telepathy and error correction for channel security and error retrieving. Quantum compression and quantum concentrating have been used for noiseless coding and teleportation techniques, respectively. Entanglement generation has been done in [66]. Moreover, [67] used quantum private communication in land quantum mobile communications. Finally, [66], [68] and [69] studied the physical properties of quantum communication channels.

1.7 Motivation

There are several challenges, trends, and aspects concurrent with deploying 5G architecture, such as optimizing the energy efficiency, enhancing radio planning, increasing the coverage of the cells, however, reducing the latency and PC are majors within the coming generations. The electricity charges for service providers and the customers, both increase linearly as the quality of service (i.e. amount of provided data) increase. The service providers aim to over an improved quality of service for the UE via providing new technologies, algorithms, and techniques by increasing the amount of deployed cells. However, this increases the amount of signalling which eventually in- creases the PC and the monthly bills, which contributes in increasing the global warming and harms the environment. Therefore, the latency is a very crucial factor, if it is decreased without increasing the power consumption, it will be a huge leap towards accessing 5G networks. Quantum solution is very effective when manipulating the time delay is required. However, such method cannot be verified unless its trade-o s, energy efficiency and power consumption are known.

1.8 Research Challenges and Objectives

This research aims to improve the state of the art (SotA) methods to enhance the network performance. Improving the latency is a main factor in terms of enabling new generations. This factor directly affects the quality of service and quality of experience of the UEs, not to mention the call drop percentage. When proposing new technique, new evaluation for the network performance will be very important. Once proposing new method, this might improve one factor of the network performance, but it might defect another factor, such as energy consumption. Subsequently, an evaluation is required to evaluate the concurrent cost, then the new method can be judged. In addition, understanding how the network factors affect each others give a new directions to optimize the available resources. In addition, most of the research within quantum field is limited to the quantum area moving along without any more examination about using quantum advancements in old style communications. In like manner, this work added to offer utilizing quantum into the classical networks below, to expand the system performance. The below objectives was concentrated on in this thesis to exceed the above challenges:

- • Modelling the power consumption of quantum-based C-RAN architecture, such model is very important to evaluate the power consumption of the proposed when compared to the SotA.
- • Modelling the latency of the SotA X2- interface and compared with the proposed quantum-based C-RAN.
- • Modelling the energy efficiency of quantum-based C-RAN architecture with the SotA method, this is necessary to give a data rate or capacity figures. This is synchronized with analyzing the trade-o s of the new addition.

1.8.1 Contributions

1. Adjusting quantum entanglement and conventional systems into one paradigm, the old style bit that is created for a specific UE is utilized to drive a LASER modulator, the last is utilized to pump a crystal, at least two photons will be produced to be conveyed, distinguished, detected and converted to classical information at the remote radio head (RRH). These photons fill in as 'prepared to utilize' copied bits that are produced without extra cost. When the UE goes to another RRH, it will be served straightforwardly by one of these bits without the need of X2-AP signalling.

2. Alleviating the amount of X2-AP signalling will diminish the time required to move the UE state starting with one RRH then onto the next. To assess such latency, investigating and analysing the conventional and quantum based handover latency have been accomplished. Alleviating the latency may acquire an extra power cost. Consequently, this work offers a simplified and parametrised power model that can be utilized to assess the quantum based systems.

3. Contrasting the quantum based handover and the classical handover procedure regarding both power consumption, time delay and energy effectiveness. The expense of the two techniques are additionally examined. Finally, this thesis offers not just handover based solution, also, it provides a general stage that can be utilized to assess the power gain, power consumption, time delay, energy efficiency and system capacity of the cutting edge techniques that can be proposed inside quantum correspon-

dences field. It is worth noting that the energy efficiency is the measure of system data rate per one Watt (bit/s/W).

1.9 Thesis Organisation

In Chapter 2, the methodology has been presented, including modelling the power consumption, delay and energy efficiency, while in Chapter 3, the results are given, as well as the conclusions, recommendations and forthcoming future trends.

Chapter 2: System Model for Quantum Cloud Networks

2.1 Introduction

Quantum computing combines quantum mechanics and physical principals to solve the problems that are not easy to be solved using classical methods, such as providing secure communications and entanglement based communications [60]. Unfortunately, the research that tackles adaptation of classical and quantum communications is yet not satisfying and resides in the early stages. This is because quantum computing research itself is also incomplete. In addition, the consistency of the two systems (classical and quantum) is totally different. Although optical communications indicate several quantum properties represented by using an optical fiber as a channel, generating the photons using a laser, and receiving the light by a detector. However, one characteristic of the photon is utilised, that is wave property, which is explained in the context of classical communication. But, the photon has two properties, wave and particle simultaneously based on how the photon is manipulated and measured [70]. Meaning, if the classical bit is represented by either 0 or 1, the quantum bit (quBit) beholds a possibility as being $|0\rangle$ and $|1\rangle$ states at the same time [71]. It is worth noticing that the advances and applications in quantum communication have been widely spreading in the last decade, such as quantum repeating [72], quantum memory [73], quantum cryptography [74], quantum routing [75], quantum synchronisation [76], quantum relay and encoder/decoder [77], and quantum entanglement [71].

2.1.1 Quantum Entanglement

A unique behaviour in quantum mechanics called quantum entanglement, it allows to transfer the quantum state of the photon immediately between two sites that are widely separated [86]. Entangled photons can be generated using spontaneous down conversion process, when a high frequency, strong beam of laser light interacts with a crystal to generate spatially entangled photons. Such theory was investigated in 1935 by Albert Einstein, Boris Podolsky, and Nathan Rosen, acronymed as (EPR), and thereafter by Erwin Schrödinger and described as EPR paradox. They considered this behaviour is impossible as the reality view is violated. Subsequently, this action was described as (spooky action at a distance) by Albert Einstein because the influence between the entangled photons travels at zero time (more than speed of light) through mysterious wave function. Nevertheless, entanglement phenomena was verified experimentally to produce such correlation in many researches such as [87], [88].

It is now possible that one classical bit can drive the laser to generate two or more entangled photons. Meaning, entanglement allows a sender to transmit two or more bits of information using only one classical bit, classically, this is not possible. Once the photons are generated and transmitted, the state of each one is not known as each one of the photons has possibility to hold, for example, a horizontal and vertical polarization at the same time, as explained earlier. After, the receiver uses a unitary operator, i.e. polarizer to force collapsing the received photon to one of its states, i.e. horizontal or vertical polarization [87]. The special characteristic about entanglement is once one of the entangled photons is measured using a particular polariser, the second photon collapses to opposite polarization state immediately, which allows us to know the information of other state on the other side. To sum up, there are two incredible entanglement properties that can be utilised in classical communications, first, more than one photon/bit can be generated from one classical bit, second, these generated entangled photons are correlated, which means any operation performed to the first photon, the other photon responds immediately. Mathematically, the two entangled photons system σ can be given as [86]:

$$|\sigma\rangle = \rho_{00}|0\rangle|0\rangle + \rho_{01}|0\rangle|1\rangle + \rho_{10}|1\rangle|0\rangle + \rho_{11}|1\rangle|1\rangle \tag{2.1}$$

where ρ_{00}, ρ_{01}, ρ_{10}, ρ_{11} are complex numbers representing the probability amplitudes, with their total probabilities $|\rho_{00}|^2 + |\rho_{01}|^2 + |\rho_{10}|^2 + |\rho_{11}|^2 = 1$, where $\rho_{00}, \rho_{01}, \rho_{10}, \rho_{11} = \frac{1}{\sqrt{2}}$, denote the probability amplitudes that the two entangled photons are holding horizontal-horizontal,

horizontal-vertical, vertical horizontal, and vertical-vertical polarization states, respectively [89]. With (ρ_{00} and ρ_{11}) $\in 0$ or (ρ_{10} and ρ_{01}) $\in 0$. It is worth mentioning that it is experimentally possible to produce up to 10 entangled photons successfully [90].

2.2 Quantum Cloud Networks

Mobile cloud network, also called cloud radio access networks (C-RAN), is proposed to seize the dramatic increase in the traffic demands, as well as providing improved quality of service [91]. The problem with cloud radio access network is that UE is required to connect to the cloud pool so as its data is processed and sent back to the target UE. Hence, a possible network delay can happen due to enlarged distances that increases the multipath delays/fading, not to mention the delay of packets processing. Another constraint is the burden on the fronthaul links regarding providing the required bandwidth for the increased number of UEs. Part of this communications is dedicated to the control plane signalling. In case of handover, there will be multiple ping-pong communications amongst UE, source BBU, target BBU, and other network units such as mobility management entity (MME) and serving gateway (SGW) to update the moving UE [92]. This issue increases the cost of time delay and power consumption due to transmitting control signals and complexity. Hence, the multiple entangles photons can be utilised to serve as main transport signals amongst the connected RRHs without the need of high level communications amongst the BBUs. The BBU pool is sending the processed data to the RRHs, then the RRHs are sending this to the UEs. If the entangled photons are generated at the pool by triggering the a laser source, a group of entangled photons can be sent to the connected RRHs. It is required to detect these photons at the RRHs side and extract the original data, as shown in Figure 2.1. Consequently, the channels between the pool and the RRHs are assumed to be optical fibre channels to ensure the required security. Once the photon is sent to its destinations and one photon is detected at one of the RRHs, it is easily now to determine the state of all other photons received by other RRHs at the same time. This situation cancels the need for noise cancellation procedure at the RRHs, such as using advanced filters to retrieve the orignal signal classically. Furthermore, no intra or inter tier communications are required because the BBU pool requires to know the detection state of one RRH only so as the others can be known. Nonetheless, in this work, the consideration of such hidden channel between the entangled photons is ignored as we are interested in the detection of multiple photons and obtaining more than one classical bits from a single bit. Hence, the procedure is to encode a classical bit into a multi-dimensional entangled photons that eventually can be detected at the receiver side as classical bits.

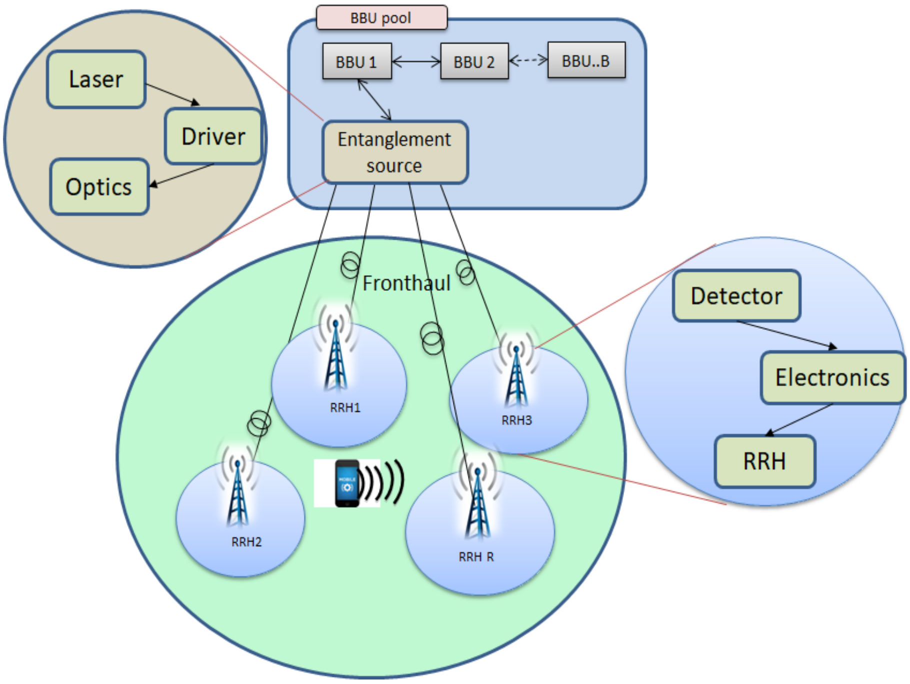

Fig. 2.1.: Cloud networks oriented quantum entanglement.

2.3 Performance Parameters

2.3.1 Quantum Based Handover Process

One of the essential problems in traditional networks is to limit the signalling overhead in the control part. An enlarged number of control plane communications causes more signalling traffic, PC, and complexity [93]. The handover process consumes considerable amount of power and causes latency that participates to call dropping and non-seamless UE's delivery from one RRH to another. Before elaborating on the proposed solution, it is worth explaining the traditional way of transferring the UE's from one RRH to another, as follows: the UE informs its serving/source RRH about the request of handover to the target RRH by examining the peak received power from all possible target RRHs through RRC measurement control signal. Then the source RRH checks the UE's willingness through RRC measurement control signal. Subsequently, the RRH with higher received power is selected as target RRH. After that, multiple connections between the source and target RRHs happen through X2AP application protocol, as shown in Figure 2.2 and Figure 2.3. These connections include resources status request from source to target RRHs, followed by a response from target to source RRH. Subsequently handover request and response between source and target RRHs. After, the status of the UE is transferred to the target RRH along with its UE data that is achieved by the GPRS tunneling protocol (GTP) data plane. Finally, the UE is updated to the new mobility management entity through S1AP protocol. It is worth mentioning the RRHs have no processing capability and the BBUs are all responsible for such procedure. The proposed quantum based method will have some advantages over traditional handover process, as follows:

1. lets assume that RRH1 is served by BBU1, and RRH2 is served by BBU2. Although the UE of RRH 1 is travelling to RRH 2, it still can be served by its serving (BBU1) as there are two (or more) entangled photons (translated to classical bits at the RRH side) are generated from UE's data. Hence, its information are copied instantly to the target RRH2, this situation can save power and time in the pool.

2. This means the travelling UE to the target RRH2 can still be served by BBU1, i.e. the target BBU is not participating in serving the coming UE, and no heavy signalling is needed, with the requirement of UE's status

transfer that is necessary for updating at which RRH the UE resides at the moment, as shown in Figure 2.4.

3. Generating several entangled photons that eventually are translated to classical bits means the cloud information are instantly received by entanglement oriented RRHs. This makes updating an establishing new services is much easier and faster than traditional method, where each RRH is allocated different set of information.

4. Interference-free channel through using optical fibres to transfer the entangled photons amongst the cloud center and the RRHs.

5. The studies have showed the X2 interface is facing an enlarged handover failure in the traditional networks, such failure is related to instability and scalability issues. Furthermore, X2 interface needs to be upgraded in all BBUs to the newest release of the standards, this matter is time-consuming and costly [94]. Hence, the entanglement can be a proper solution to overcome the scalability issue.

6. Traditionally, not all the BBUs have direct X2 interface installed amongst them, when no X2 interface is found, S1 interface is the replacement. The two BBUs will be connected to the MME unit to perform handover. In such case, the entanglement procedure represents a perfect replacement of X2 and S1 to achieve the handover.

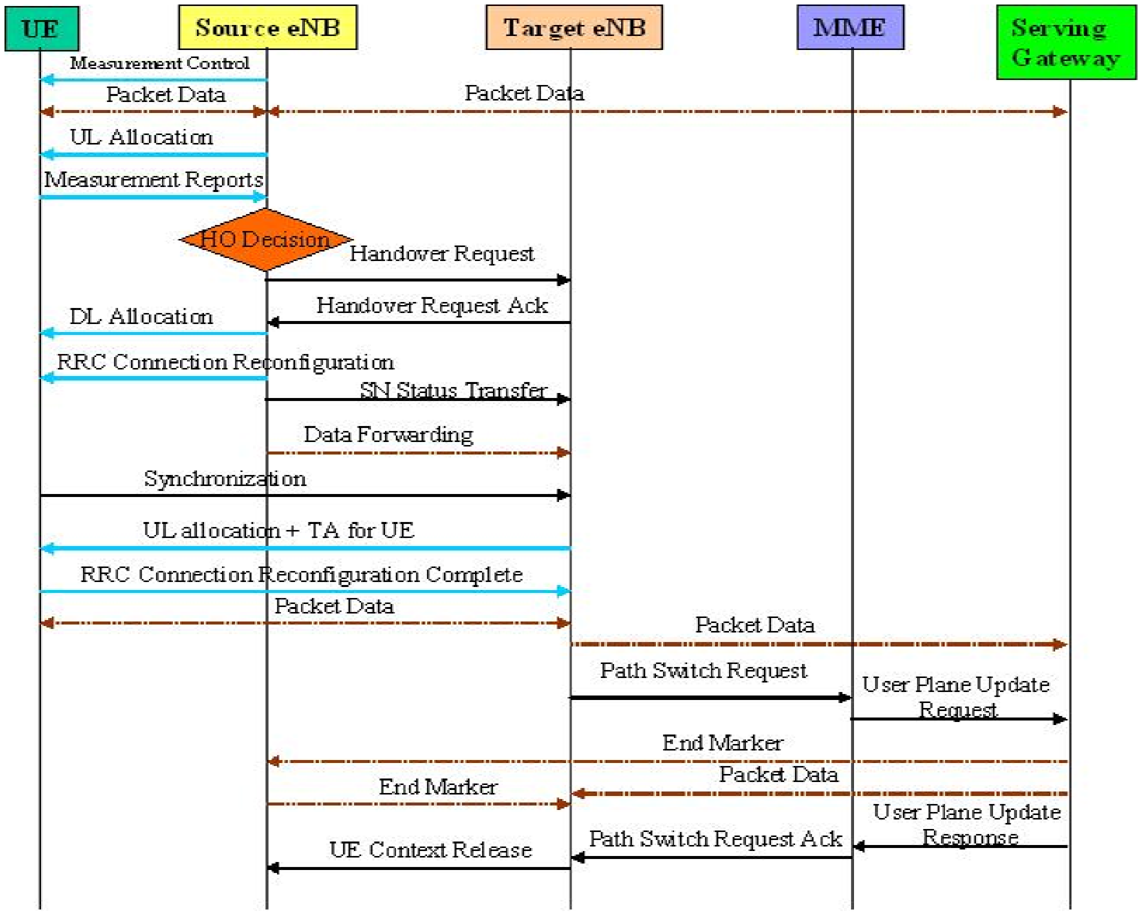

Fig. 2.2.: The signalling procedure of traditional mobile network handover.

2.3.2 Quantum Energy Efficiency

The general formula of the classical entropy is defined as the average amount of information that is received from an information source. In other words, it is the sum of the probabilities of the generated symbols, i.e.

$$H(x) = \sum_{i=1}^{M} pr_i \log_2 pr_i \tag{2.2}$$

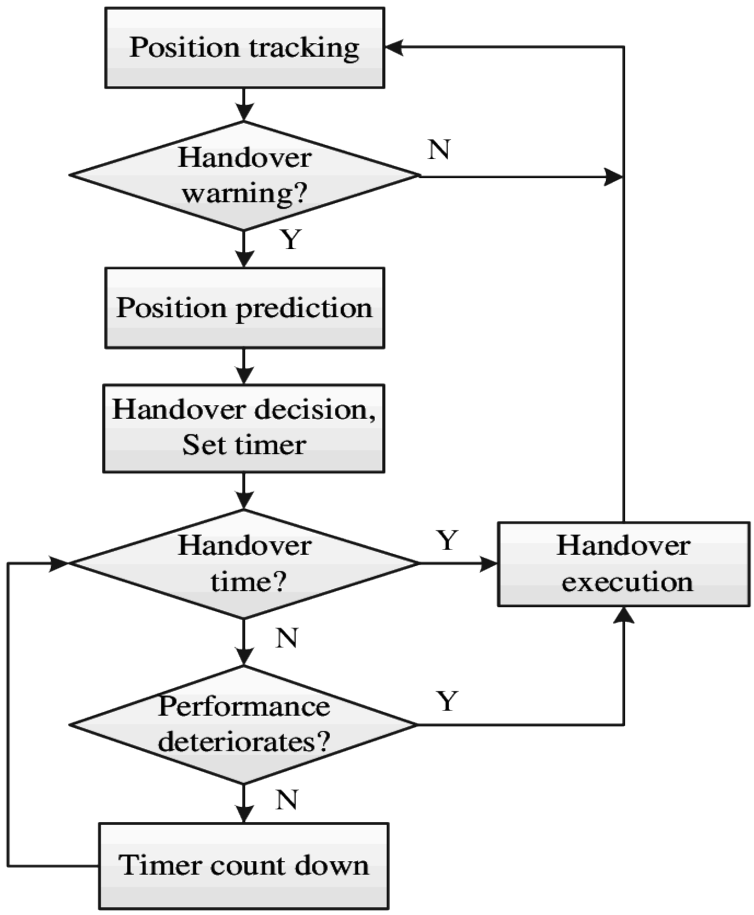

Fig. 2.3.: The signalling flow chart of traditional mobile network

where M denotes the total number of symbols, and pr_i is the probability of receiving symbol (i). For example, the entropy of a coin with two symbols, each with 0.5 probability, produces 1bit of information. The quantum analogue of the classical entropy is formulated by Von Neuman Entropy, it can be given as

$$H(x) = \sum_{i=1}^{I} \lambda_i \log_2 \lambda_i \tag{2.3}$$

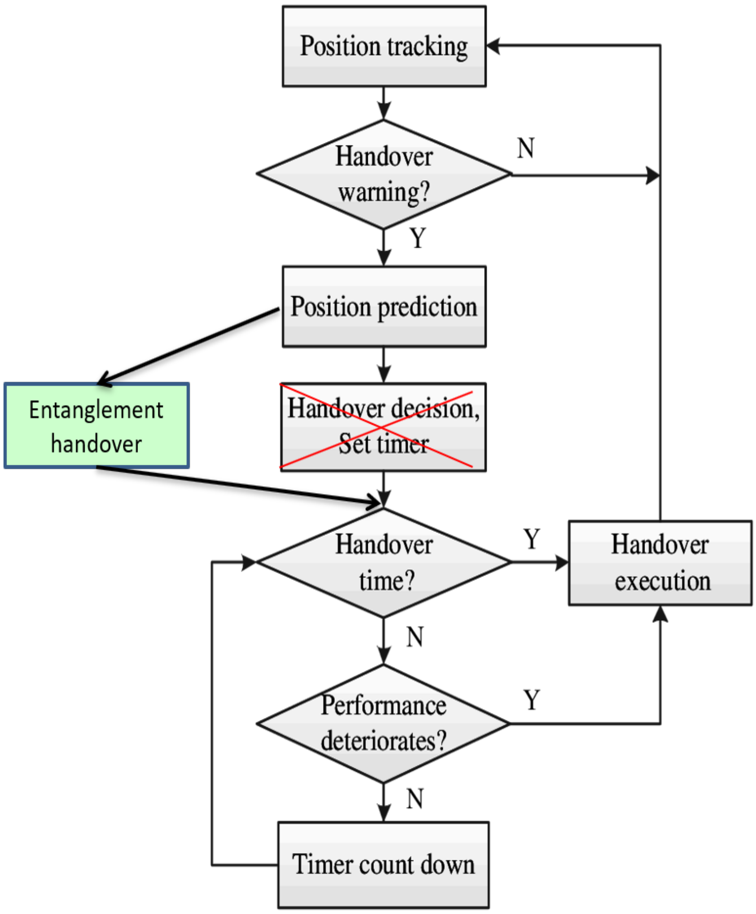

Fig. 2.4.: The signalling flow chart of entanglement based mobile network

where I is the total number of system states, λ_i is the eigenvalue of the state i [95]. Since we are interested in quantifying the energy efficiency of quantum-classical system, we have modified the entropy in terms of received power at the RRH, along with eigen values of the system. We have assumed the power associated with each transmitted photon state is p_i, hence, the entropy is given as

$$H(x) = \sum_{i=1}^{I} p_i \lambda_i \log_2 p_i \lambda_i \tag{2.4}$$

$$H(x)/sec = W\ log_2(1 + SNR) \tag{2.5}$$

Where $H(x)/sec$ represents the capacity of the system. Subsequently, the received quantum energy efficiency at the UE end (Q_{ee}) from the cloud center is given by

$$Q_{ee} = \frac{W\ log_2(1 + SNR)}{P_{QC}} \tag{2.6}$$

Where

$$SNR = \frac{P^t_{n,u} h_{m,u} r_{m,u}}{B\ N_o} \tag{2.7}$$

is the wireless signal to noise (SNR) ratio, W is the system bandwidth. In addition, $P^t_{n,u}$ is the power transmitted from RRH n to UE u, $h_{m,u}$ represents the channel gain from n-th RRH to u-th UE, and N_o is the AWGN received by the UE. In addition, $r_{n,u} = d^{-\alpha}_{n,u}$ denotes the path loss between RRH n and UE u, α is the path loss exponent. Furthermore, $d_{n,u}$ is the straight line distance between n-th RRH and u-th UE, which is given as

$$d_{n,u} = \sqrt{(x_n - x_u)^2 + (y_n - y_u)^2} \tag{2.8}$$

where x_n, y_n, x_u, y_u indicate the Cartesian x and y axes of the RRHs and UEs, respectively. Moreover, P_{QC} is the PC of the system which is modelled in Section 2.3.3. In addition, the optical power received by the RRH from the cloud center when each photon's state is associated with its own probability $|\langle\beta|\alpha\rangle|^2$, can be given as:

$$P^r_{n,u} = P_{PA} \times \frac{p_{i,n,u}(|\langle\beta|\alpha\rangle|^2)_{i,n,u}}{A_{i,n,u}} \tag{2.9}$$

where P_{PA} denotes the received signal power amplification at the RRH side. Furthermore, $p_{i,n,u}$, $A_{i,n,u}$ denote the power and attenuation, respectively, of the signal corresponding to state i while travelling to RRH n that is associated to the UE u through the optical fiber channel.

2.3.3 Quantum Cloud Power Consumption

It was assume the total PC of the network is denoted as P_{QC}. The PC of the classical side of the cloud network is P_{cloud}, while the PC of quantum entanglement side is $P_{enanglement}$, where:

$$P_{QC} = P_{cloud} + P_{enanglement} \tag{2.10}$$

The cloud side itself contains many base band units servers that are responsible for processing the base band packets of the UEs. Each server's PC is denoted as P_{server}, where

$$P_{cloud} = S \times P_{server} \tag{2.11}$$

as S indicates the number of BBU servers. On the other hand, the quantum part of the cloud ($P_{enanglement}$) is consisted of laser's PC (P_{laser}) and detector's PC ($P_{detector}$). Hence, the entanglement PC is given as

$$P_{enanglement} = L \times P_{laser} + D \times P_{detector} \tag{2.12}$$

where L and D denote the number of Lasers and detectors, respectively. It is worth mentioning that other optical units within the paradigm of entanglement generation are not power consuming, such as BBO crystal, beam splitter, attenuation units, etc. P_{QC} is also subjected to the effects of other losses found within the server construction, such as, AC-DC, DC-DC and cooling loss. These losses are linearly scaled with other units' PC and approximated by using loss factors (σ_{DC}, σ_{AC}, σ_{cool}) to represent AC-DC, DC-DC and cooling, respectively [96]. Successively, the total PC of quantum cloud (P_{QC}) is updated as the combination of cloud PC and its losses PC:

$$P_{QC} = \frac{P_{cloud} + P_{enanglement}}{(\sigma_{DC})(\sigma_{MS})(\sigma_{cool})} \tag{2.13}$$

The other part of the modelling is related to the RRH's PC (P_{RRH}). The RRH is also constructed of many units, it is modelled as:

$$P_{RRH} = \frac{P_{PA} + P_{RF} + P_{detector}}{(\sigma_{DC,R})(\sigma_{MS,R})} \tag{2.14}$$

Where

$$P_{PA} = P^{t}_{n,u}/\eta_{PA} \tag{2.15}$$

is the PC of the power amplifier and η_{PA} is its efficiency. In addition, $\sigma_{DC,R}$ and $\sigma_{MS,R}$ represent RRH's DC and RRH's MS loss factors, respectively, finally, P_{RF} is RF unit's PC. Subsequently, the total network PC is given as the combination of quantum-classical and RRH part, as follows:

$$P_Q = P_{QC} + P_{RRH} \tag{2.16}$$

2.3.4 Delay Analysis

In cloud networks, the total time delay of handover will be little less traditional networks as the BBUs are located in one place [97]. Although orders of ms time delay seems insignificant. However, in a view of mobile communications, such delay is considered large and it is inherently originated due to the protocol stack multiple communications and processing. This is because the processing delay is much higher than link delay no matter how far the BBUs are placed. To model the delay, we have assumed the link delay from RRH to the pool is

$$\tau_{n,o} = d_{n,o}/c \tag{2.17}$$

Where (o) denotes the pool's geographical position that is assumed to be at the origin of area of interest where the cloud centre resides, where $d_{n,o} = \sqrt{(x_n - x_o)^2 + (y_n - y_o)^2}$, where x_n, y_n, x_o, y_o indicate the Cartesian x and y axes of the RRHs and cloud centre, respectively. c is the speed of light. In case of optical fiber links

$$\tau_{n,o} = d_{n,o}/c_{opt} \tag{2.18}$$

Where $(c_{opt} = c/ind)$ is the speed of light inside the optical fiber, and (ind) is its refractive index. Subsequently, the delay from the UE to the RRH is denoted as

$$\tau_{n,u} = d_{n,u}/c \tag{2.19}$$

This link is only wireless.

The work in [98] has mentioned that the execution/processing time is linearly proportional to the processed RBs and modulation coding scheme (MCS) that is used to transmit these RBs. Therefore, a model is required to combine such concepts. If we assume (τ_{BBU}) is the execution time of the BBU processing, where

$$\tau_{BBU} = \tau^{int} + (mod * RB) \tag{2.20}$$

Where τ^{int} represents the initial device delay due to other functions rather than MCS, the latter is denoted by the constant factor (mod) which indicates the degree of increment. Hence, the total delay of traditional network can be expressed as

$$\tau_{traditional} = \tau_{n,o} + \tau_{n,u} + \tau_{BBU} \tag{2.21}$$

where the handover via X2 interface is assumed to be embedded within the total BBU server processind delay, i.e. τ_{BBU}.

If entanglement case is discussed, source/laser and detector are also found within the BBU pool and RRHs. Hence, their delays are added to the total formulation of entanglement case, as follow:

$$\tau_Q = \tau_{n,o} + \tau_{n,u} + \tau_{laser} + \tau_{detector} + \tau_{BBU} - \tau_{\Delta} \tag{2.22}$$

Where τ_Q represents the total delay of quantum scenario. In addition, τ_{laser}, $\tau_{detector}$ are the time delays of the laser source and detector, respectively. τ_Δ denotes the delay gain when deducting the delay of handover process, that is assumed as 10% of the BBU server delay, i.e.

$$\tau_\Delta = \tau_{BBU} - \tau_{BBU} \times 0.9 \tag{2.23}$$

This gain is from one BBU processing, this gain can be further extended to as many as the number of entangled photons as each entangled photon represents an elimination for X2 interface in the tagged BBU. For example, when we have 4 entangled photons, this means the delays of 4 BBUs are mitigated, and so on. Subsequently, the delay gain will be equivalent to

$$(|\sigma\rangle \times \uplus)(\tau_\Delta - \tau_{laser} - \tau_{detector}) \tag{2.24}$$

where $\uplus$ denotes the number of entangled photon pairs.

2.3.5 Power Gain Analysis

The more entangled photons are used, the more saving in the power can happen. The UE that is travelled from one cell to another can still be served permanently from its original BBU until it reaches the maximum number of served UEs. In this case, the UE will be handed to the target cell in a relaxed period of time. If the same UE is also moved to another cell, the same procedure is still valid, this situation can happen as long as the BBUs reside within the same BBU pool. Once the UE moved to another BBU pool, inter-BBU pool handover is required.

However, this work only discusses the case of single BBU pool with group of BBUs. Generally, the PC of the network is divided to two parts, static and dynamic. The static part is the amount of power consumed when there is no transmitted power or processed resource blocks. This type of PC is unavoidable and non reduce-able since it is only responsible for operating the device/server itself. On the other side, the dynamic PC totally depends on the transmitted power to the UEs or the processed load/packets. Therefore, once the transmitted power is reduced or the number of served UEs are reduced, this dynamic type of consumption will be alleviated. The transmitted power from the BBU pool can be received by a number of RRHs that are equivalent to the number of generated entangled photons. This situation can save power and replaces the case of generating separate data for each RRH. It also reduces the number of entanglement sources, for example 8 entangled photons can serve 8 RRHs at the same time. These 8 RRHs are no longer needed to generate data for the new arrival UE, rather, directing the received UE data from the sending BBU to target RRH, then to the UE. Accordingly, the X2 PC is deducted from the cloud PC when using entanglement case. Hence, we have assumed the amount of power consumed by X2AP protocol is (P_{Δ}). Subsequently, the total cloud PC is updated:

$$P_{QC} = \frac{(P_{cloud} - P_{\Delta}) + P_{enanglement}}{(\sigma_{DC})(\sigma_{MS})(\sigma_{cool})} \tag{2.25}$$

where P_{Δ} is the gain in the PC:

$$P_{\Delta} = P_{BBU} - 0.8 \times P_{BBU} \tag{2.26}$$

2.4 System Complexity

There are several limitations regarding adapting quantum methods into the more convenient traditional or cloud networks. Generally, the cost of installing and managing the complexity of entangled photons generation can be higher than the cost of installing ordinary optical fiber based mobile cloud networks, where the photons can be dealt with as classical bits only. Since this work only used the duplicate entangled photons to provide the necessary UE information in time without any cost, there still another characteristic of the entanglement theory is not yet utilised, i.e. the correlation channel amongst the entangled photons. Utilising the quantum hidden channel of entangled photons can offer a solution in case one of the photons is highly attenuated or not detectable. By using feedback signals amongst the tagged RRHs, each one can reveal its detected photon state and what time it is received. When a particular RRH did not detect its photon at the allowed time slot, the other RRHs can share their states to compensate the missing information of the tagged RRH. However, this type of communications require an advanced protocol and dedicated algorithm to manage the feedback signals of the participating RRHs. In addition, implementing the quantum methods requires more caring while setting up the hardware equipment, also it requires more maintenance. It is worth noticing that this research has used Matlab software to simulate the proposed model and produce the results.

Chapter 3: Results, Analysis and Conclusions

3.1 Results and Analysis

The detector expends negligible power, with only 16 mA and 11 V of voltage, that is around 1 W of intensity. Also, at that point, the response of the detector is expected around 11 ns, while the latency of the laser driver is 1.1 μsec, as mentioned in Table 3.1. It was referenced in [44] the control plane may reach 100 ms. Be that as it may, we used worst case scenario, that the handover is expected to take just 10 μsec. Consequently, the latency increasing will be $\tau_\Delta - (\tau_{laser} + \tau_{detector})$ as depicted in (2.24). Since τ_Δ is bigger than the latency of both, the laser and detector, at that point the latency gain can reach 9 μsec if latency of the links $(\tau_{n,o} + \tau_{n,u})$ are the equivalent for entanglement and traditional.

As necessities be, Figure 3.1 presents the latency correlations of conventional and quantum cases while handling bunches of resources when the network created 4 photons. In the event that more resource are prepared, the delay turn larger in light of the fact that the dynamic postponement is directly identified with the resource blocks, as investigated in Section 2.3.4.

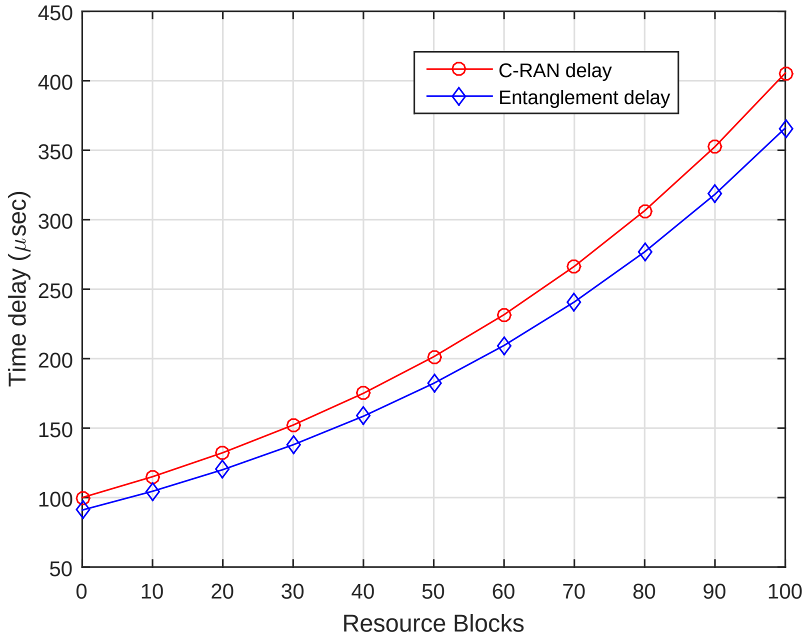

Fig. 3.1.: Time delay of quantum entanglement and C-RAN for several resource blocks.

Note when the quantity of photons is expanded, at that point sparing in the latency can be expanded as well. In like manner, Figure 3.2 shows the postpone saving something aside for various quantities of photons when preparing comparable measure of resource blocks in Figure 3.1. In the event that the quantity of photons expands, each RRH's postpone will be further spared, which clarifies why all the more saving occurs inside the quantum case as the quantity of created photons is expanded.

With respect to PC, the signalling expends extensive measure of intensity, it arrives at 20% to 80% for the CPU [44]. Thinking about

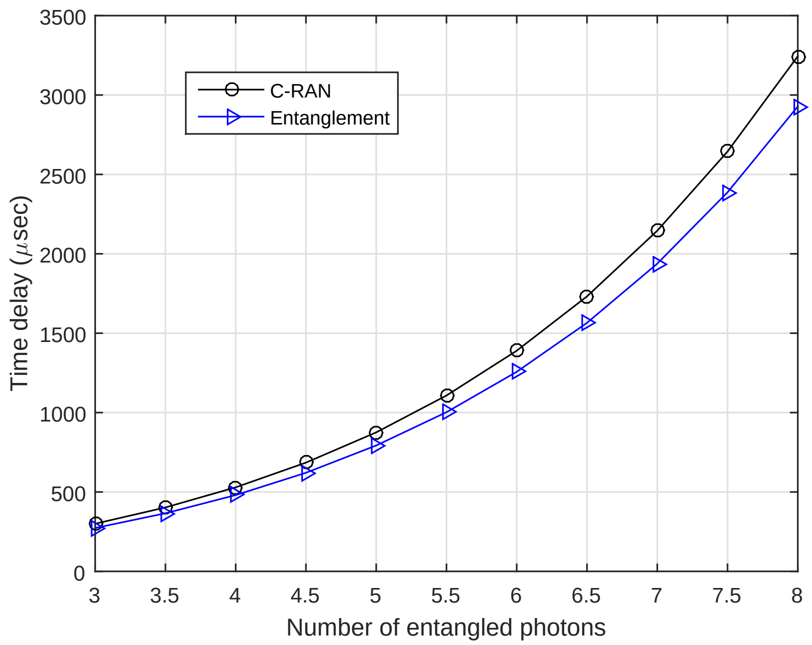

Fig. 3.2.: Times delay of quantum and traditional C-RAN when generating up to 8 photons.

the measure of power added to C-RAN framework by means of the detectors/lasers, examination the two frameworks is vital. Consequently, Figure 3.3 shows the PC correlation for various tallies of BBU and RRH, accepting the overhead of handover just 20% of BBU utilization. Additionally, we expected each BBU is associated with one laser/detector, same methodology remains constant for the RRHs. It very well may be indicated that a somewhat expanded in the quantum PC in examination with traditional cloud when the quantity of lasers/detectors is high.

However, such cost can be mitigated in two folds: first, practically, the number of lasers can be reduced as one driving laser can feed as many as the entanglement based RRHs, which saves more power by using one

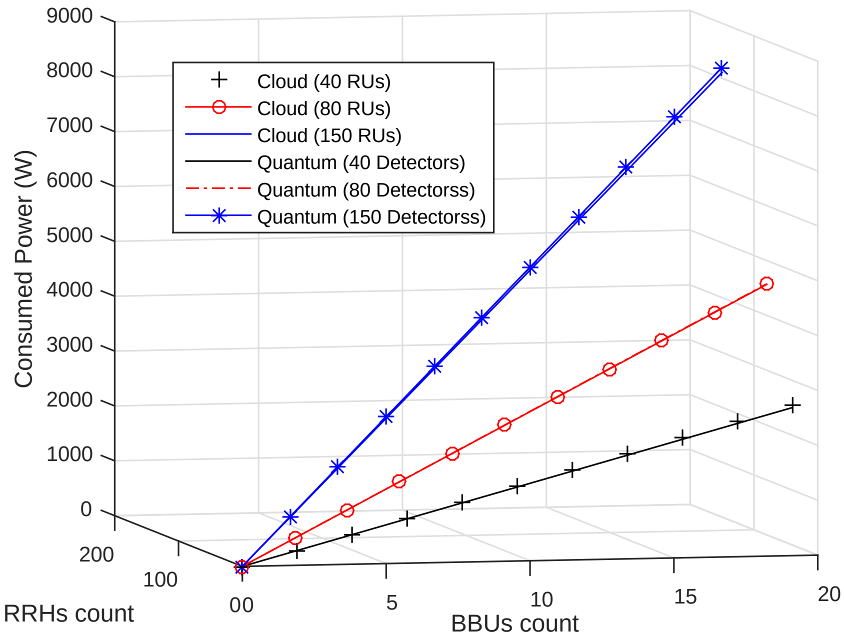

Fig. 3.3.: Power consumption of C-RAN and quantum entanglement based C-RAN for different number of RRHs and BBUs.

entanglement source for several RRHs. Second, the signalling overhead can be increased to more than 20% as mentioned in [44]. Hence, Figure 3.4 shows the PC comparison for different percentage of signalling overhead (BBU utilization) while holding the same number of RRHs of Figure 3.3. It can be shown the PC of quantum case is less than traditional C-RAN.

The PC can affect the energy efficiency of both systems. Once the PC is increased, the energy efficiency is decreased. We have assumed the optical fiber channel has no effect up on the signal level, i.e., $A_{i,n,u} = 1$. In the literature, there are different type of channels. However, any type of channel can be used for both systems will have equalised effect, hence, the channel is assumed ideal. However, this is further compromised by

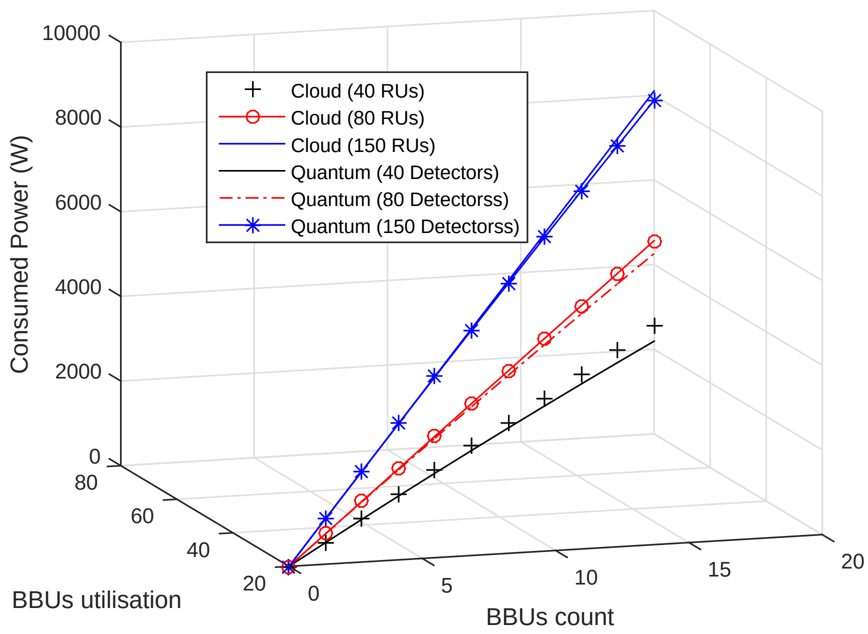

Fig. 3.4.: Power consumption of C-RAN and quantum entanglement based C-RAN for different number of BBUs and its utilization percentage.

not adding power gain to the received signal by the RRH so as both effects can be equalised, i.e. $AP = 1$. Successively, Figure 3.5 shows the energy efficiency comparison of both C-RAN and quantum entanglement based C-RAN, for different number of RRHs and processed resource blocks. It is clear the more processed resource blocks means more power consumed in the BBU, which indicates less received energy efficiency at the UE's level.

To elaborate more about the values of Figure 3.5, we used equations (2.11) and (2.10) to calculate the power consumption of traditional and quantum based cloud. In the latter, the total number of BBU servers is taken as 20, this is multiplied by the 80% utilization of the PC of each server (29.4), which results ($20 \times 23.52 = 470.4W$). In addition to this consumption, we have added the value of RRH, as in equation 2.14. The RRH PC is equal to ($12.9 + 29.65 + 1 = 43.55W$), this value is multiplied by the number of RRHs (40), then the total PC of the RRHs is equivalent to ($40 \times 43.55 = 1742$), this value is added to the power of BBU servers, which results about ($2212W$). Adding to this value the PC of the cooling, DC and MS conversions, the total PC will be about 2500, as depicted in Figure 3.5. Since the PC of both cases is relatively equalised, their EE performance is relatively identical.

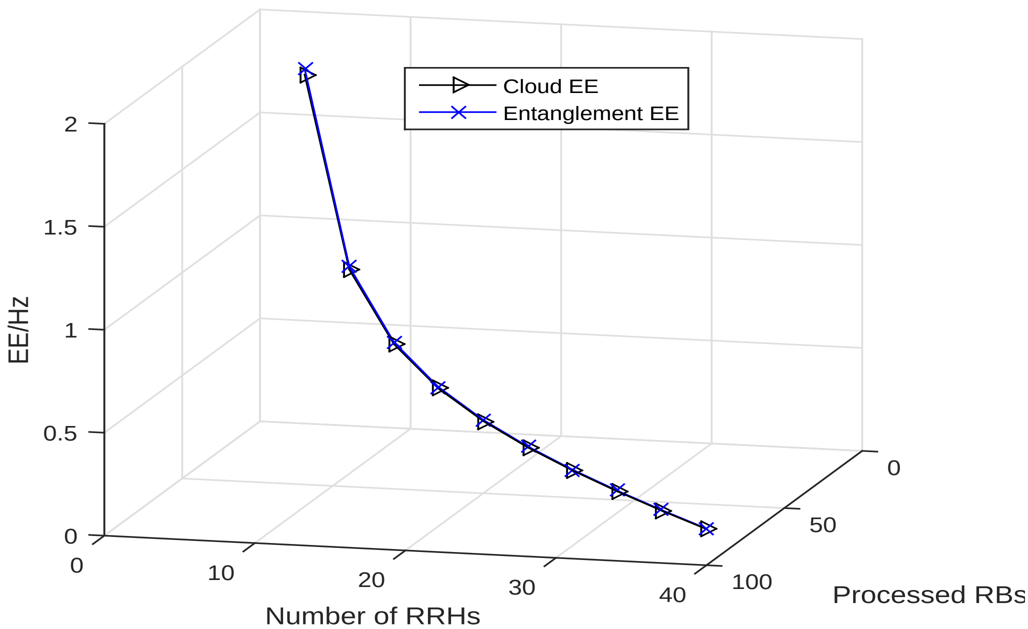

Fig. 3.5.: Energy Efficiency of C-RAN and quantum entanglement based C-RAN for different number of RRHs and processed resource blocks.

Factor	Traditional(Generated)	Unit
σ_{DC}	0.910	-
σ_{MS}	0.9250	-
σ_{cool}	0.90	-
$\sigma_{DC,R}$	0.910	-
$\sigma_{MS,R}$	0.9250	-
ind	1.3	-
mod	0.014	-
α	3	-
$A_{i,n,u}$	1	-
AP	1	-
P_{RF}	12.9	W
$P_{detector}$	1	W
P_{laser}	1	W
P_{PA}	29.6528	W
P_{BBU}	29.4	W
τ^{int}	50	μsec
τ_{laser}	1	μsec
$\tau_{detector}$	1	$nsec$
N_o	$\frac{dB}{Hz}$	-10

Table 3.1: Quantum Cloud Network System Model [96], [99].

3.2 Conclusion and Future work

1. This work has showed that quantum computing can be utilized as a solution for the classical cloud mobile networks.

2. This work proposed an evaluation and futuristic solutions the cloud based cellular communications, particularly for C-RAN. The traditional cloud networks encounter an enlarged delay due to handover process via X2AP protocol. Therefore, this thesis showed that quantum entanglement phenomena can be used to decrease such cost through modelling the latency of both paradigms.

3. Without any compromisation of PC, this work showed that a quantum based paradigm can boost the energy efficient of the traditional cloud network, with a possibility of power saving when using more entangled photons.

4. This work also allowed inter-BBU pools entanglement based handover when the handover participating BBUs reside on different pools, the source BBU can still serve the travelling UE while the background communications to update the UE's position happen in a relaxed period of time.

5. When there are few UEs in the target RRH and some of them are still being served by source BBU, the residual UEs of the target BBU can be handed over to the source BBU by using resources sharing algorithm to switch off the target BBU and save power, which further improves the energy efficiency of the system.

Cloudification alongside qunatum computing, are a vital to enhance the EE in the data centers. To achieve the required EE without compromising the performance, in the future, many works can be done, such as:

1. The matter of optimising the number of RRHs that one server can hold is a vital to reduce the number of entangled photons, which reduces the complexity. Such complexity can come from the fact the more entangled photons, the more complicated protocols stacks and advanced algorithms needed to manage the process of correlation channel management.

2. The above matter can put forward another future work related to the trade-offs amongst the power consumption and complexity of such algorithms, that can be compared to the EE calculations of the traditional cloud networks.

3. Finally, the placement of the virtualised Entangled source in such architecture can represent another crucial issue. The optimal position of the entangled source that can be in one of the RRHs rather than the pool may offer an enhanced EE.

4. As the UEs resources assignments entities and set-ups functions are placed far away from the UEs in the pool, the problem of placing the BBU pool becomes a prerequisite to ensure that these functions' signals reach the RRHs without any extra delay. This eternally influences the network performance regarding the EE. Such optimization could also improve the transmission power to the RRHs to provide a higher coverage with less energy consumed. This in turn leads to an efficient network that is an important property of the future 5G networks.

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