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Challenges of Bandwidth and Power Limitations in Cellular Communication: A Review

Ikechukwu H. Ezeh[1], Isaac A. Ezenugu[2]
[1]*Department of Cyber Security, Federal University of Technology, Owerri, Imo State, Nigeria.*
[2]*Department of Electrical & Electronic Engineering, Imo State University, Owerri, Imo State, Nigeria.*

Abstract
To accommodate the current huge demand for wireless services and the anticipated future growth, there is need to review the factors affecting wireless channel capacity and techniques that can improve capacities of wireless communications. The key resources of wireless communication are available bandwidth and signal power. But these resources are limited; which in turn limit the carrying capacity of wireless system. The major reasons for their limitations are government regulations of the transmission bandwidth and the low powered devices of wireless systems. The limited wireless resources have driven operators to seek for techniques that enhance channel capacity. But each technique or method adopted comes with its own challenges. In this paper, the limiting factors affecting wireless channel capacity are discussed. In addition, various techniques developed to enhance wireless system capacity and the limitations of each of these techniques are reviewed.
Key Words: *Bandwidth, Power Limitation, Wireless Channel Capacity, Wireless Resources*

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I. Introduction

According to report by [1], the amount of data being conveyed by mobile networks is growing between 25% and 50% per year and this growth may last beyond 2030. To accommodate the current huge demand for wireless services and the anticipated future growth, there is need to review the factors affecting wireless channel capacity and techniques that can improve capacities of wireless communications.

Wireless system capacity depends largely on two resources – bandwidth and the signal power. Due to some constraints, these resources are limited. The limitation of these resources in turn limits the carrying capacity of wireless system [2]. According to [3], part of the answer in coping with exploding demand for wireless data is technological innovations, while the other part is better spectrum policy. Thus to cope with exploding demands for wireless services requires the review of various factors and techniques that influence or enhance system capacity. In this paper, we discussed limiting factors affecting wireless (cellular) channel capacity. We also reviewed various techniques developed to enhance wireless system capacity and the limitations of each of these techniques.

II. Overview

The key resources of wireless communication are available *bandwidth* and signal *power* [4]. These resources are known to influence the capacity of a communication channel. It was noted by [5] that wireless communications are typically characterized by great constraints on these resources as well as by rapid fluctuations in their availability. For instance, bandwidth limits the spectrum of transmitted signal and provides a measure of the extent of significant content of a signal. Since electromagnetic spectrum is limited, it should be utilized efficiently. Spectral efficiency is also known as bandwidth efficiency, and it describes the information rate that can be transmitted over a communication system bandwidth. Though many researchers consider *bandwidth efficiency* as more important efficiency criterion, the authors in [6] pointed out that those techniques which improve *power efficiency* should not be classified as less efficient since they are capable of affecting the capacity of the system. According to [4], in many communication systems, one of these resources may be more valuable than the other, thus such systems may be classified as either *bandwidth limited* or *power limited*.

The fundamental characteristic of a wireless channel that defines the channel's maximum possible data rate is the channel capacity. There are two basic approaches to increase the channel capacity. One basic approach to increase wireless channel capacity is to use more bandwidth, because channel capacity is directly proportional to the channel bandwidth. But wireless spectrum is highly regulated and expensive, thus increasing channel capacity by increasing the bandwidth comes with huge cost. The second basic approach to increase channel capacity is to increase the signal power. But increasing the signal power reduces the battery life of mobile devices. In addition it may introduce interference to adjacent channels.

Beside these two basic approaches, other methods to increase channel capacity include development of techniques that will utilize the available bandwidth and employment of power control schemes to maximize the channel capacity. But these techniques have their limitations. Because of these limitations, attention is being given to developing strategies that will achieve transmission data rates close to wireless channel capacity [7].

II.1 Wireless Channel Capacity

Channel capacity is the maximum amount of information that a communication channel can carry per unit of time, thus is measured in bits per second. Channel capacity is related to signal bandwidth, received signal power and noise. Equation (1) shows the mathematically statement of Shannon's Law [8]:

$$C = B.log_2\left(1 + \frac{S}{N}\right) \qquad (1)$$

Where C is the maximum capacity of the channel (or Shannon's capacity limits for the given channel) in bits per second, B is the bandwidth of the channel (in Hertz), S is the signal power (in Watts), N (also in Watts) is the noise power. The ratio (S/N) is known as the signal to noise ratio (SNR). From Shannon's law we can infer that the channel capacity increases with the increase in bandwidth and improvement in signal to noise ratio. Thus Shannon's law tells us that we have few parameters (i.e. the bandwidth and the signal to noise ratio) to adjust in order to increase the capacity of a given channel. This implies that the allocated bandwidth and the signal to noise ratio have to be traded against each other in order to increase the capacity of a channel.

II.2 Limited Wireless Network Resources

The major resources of wireless systems - bandwidth and signal power are limited. The major reasons for their limitations are government regulations of the transmission bandwidth and the low powered devices of mobile communication systems. The consequence of high demand for connectivity availability and number of services that run on mobile devices is the striking increase in the utilization or consumption of these network resources.

As pointed out by [9], exponential increase or growth in consumption of network resource demands corresponding rapid increase in the availability of the resource itself. Though wireless spectrum unlike materials resources are renewable and cannot be exhausted or used up in terms of consumption, but as wireless capacities approach the limit defined by Shannon's law, it will be difficult and costly to achieve or realize gain. The limited wireless resources have driven wireless operators to seek for methods or techniques that enhance channel capacity. But each technique or method comes with its own challenges.

III. Challenges of Limited Wireless Resources

From Shannon's law stated in equation (1), we observe that there are two basic approaches to increase the capacity of a wireless channel. One is by increasing the amount of channel bandwidth, the other is by increasing the signal-to-noise ratio (SNR). Theoretically, these two approaches are correct, but they have practical limitations. To maximize channel capacity for wireless systems, various methods and techniques have been adopted over the years. According to [10], the capacity of any wireless network is a function of three key elements, namely, the *spectrum* used to deliver the service, the *technology* which delivers bits over the wireless medium, and the *topology* of the cells which make up the network.

But no matter the view or approach adopted to expand wireless network capacity, the fundamental truth remains that though the techniques or technologies employed under such methods can offer significance increase in channel capacity, they come with some challenges. In this paper, the challenges of limited wireless resources will be discussed with considerations from Shannon's law and various techniques adopted to increase wireless network capacity.

III.1 Considerations from Shannon's Law

Shannon's law relates the channel capacity to the channel bandwidth, signal power, noise and interference. We briefly discuss the limitations and the challenges posed by these factors.

(a) Bandwidth Constraint

Though Shannon's law implies that increase in bandwidth should results in proportionate increase in capacity, but practically it is not so. This is because increasing the bandwidth also increases the noise power. Thus as bandwidth goes to infinity, the capacity is not finite.

(b) Adjacent Cell Interference

Shannon's law suggests that apart from the bandwidth, the other variable that can be adjusted to increase the channel capacity is SNR. To increase SNR means that the signal power must be increased. But increasing the signal power in order to increase the SNR (and hence the channel capacity) results in adjacent channel interference. The consequence of inter-cell interference is that the SNR for user devices are lowered, hence limiting the channel capacity.

(c) Energy Constraint

In addition to adjacent channel interference associated with increasing signal power, mobile devices are energy constrained. The transmitted power of mobile devices is constrained by battery size and life. The author in [11] pointed out that in cellular network; the power received at the base station is limited by the battery life of a mobile device that communicates with the base station. Thus at the edge of cell coverage area, what limits the transmission capacity is not the amount of bandwidth, but the strength of the transmitted signal from the mobile device as received at the base station. Furthermore, increasing the power of mobile devices in order to increase SNR, significantly decrease the length of time that a device can be operated without replenishing the energy either by replacing or recharging the battery. Also the transmitted power of mobile devices is in some cases constrained by regulations, i.e., specification of the limits of human exposure to surrounding radio frequency signals.

III.2 Techniques to Increase Wireless Capacity

In this sub-section, we look at the techniques that can enhance or improve channel capacity and the challenges facing each of them. Most of these techniques maximize the utilization of available bandwidth or spectrum to improve wireless channel capacity.

(a) Wireless Spectrum Allocation

Government regulations specify the bandwidth and the type of information that a user can transmit over designated frequency bands. Thus the spectrum used for wireless communication is limited and in a given location are shared by all users. The implication is that we have limited amount of bandwidth to assign to a given channel [9]. In addition, frequency allocations were largely done before the wide use of wireless communications. For instance, cellular systems spectrum is confined in the Ultra High frequency (UHF) radio range of spectrum which ranges from 300 MHz to 3000 MHz (3 GHz). It is evident that that the whole range of UHF is not available for providing cellular wireless access. This is because a great portion of this spectrum range have been allocated to other communication services such as radio and television broadcasting, Global Positioning System (GPS), weather radar system, air navigation systems, etc. Thus, due to regulations, only a fraction of the spectrum range of 300 MHz to 3 GHz is available for provision of cellular wireless access [9], [11].

The scarcity of spectrum is an artificial limitation or constraint caused by the current stand or position towards spectrum management [6], [12], [13]. To solve the problem of scarce spectrum for wireless access created by government regulations, the authors in [9] suggested a complete re-allocation of usable spectrum. Though such complete re-allocation of the usable spectrum could provide efficient bandwidth utilization, but it would require the assent and full cooperation of the stakeholders which include the government spectrum regulatory bodies, present licensed spectrum users who have invested huge financial resources to acquire the spectrum and users such as the military that require dedicated spectrum. Thus complete re-allocation of the usable spectrum is unlikely given that the stakeholders have divergent interests and requirements.

(b) Antenna Techniques

Antenna techniques that have been adopted to increase wireless channel include Multiple Input Multiple Output (MIMO) technique, Space Coding and Multi-user MIMO (MU-MIMO) [10], [9]. MIMO technology employs multiple antennas at both the transmitting and receiving devices. With MIMO techniques, multiple concurrent transmission streams may be sent between the base station and the user equipment (UE), hence increasing throughput over a given amount of spectrum [2]. MIMO improves channel capacity without the need to increase the transmission power [14].

Furthermore, [9] pointed out that in an ideal situation, MIMO can in essence increase the channel capacity linearly as the number of antennas used increases, as suggested by equation (2).

$$C = B.a.log_2\left(1 + \frac{S}{N}\right) \quad (2)$$

Where a is the number of antennas.

Though MIMO has contributed to significant increase in spectral efficiency for wireless connectivity in recent times, it comes with some challenges. As noted by [2], placing multiple antennas at UE could be problematic. Placing two antennas at UE may not pose much problem, but placing higher order MIMO to achieve more spectral efficiency demands that the UE would be physically larger and power consumption enormous. Also, more antennas at base stations imply high equipment and electric power cost. In addition, to achieve maximum spectral efficiency, the transmitting and receiving equipment must have perfect instantaneous knowledge of the state of the channel information, which is impractical in real situation. Thus, in some situations, the burden of costs and complexity introduced by additional antennas in MIMO technology outweighs the marginal gains obtained from it [2], [9], [15], [10].

Traditional MIMO system is often referred to as Single User-MIMO (SU-MIMO) or point-to-point MIMO. In MIMO system, the base station or the access point communicates with one UE, and each is equipped with multiple antennas [14]. An extension of MIMO is the Multi-user MIMO (MU-MIMO). Similar to SU-MIMO, in MU-MIMO, the base station and UE have multiple antennas, but in contrast to SU-MIMO, the base station is able to communicate with several UEs. The authors in [14] pointed out that in using MU-MIMO, the system capacity or performance is improved because multiple users could simultaneously communicate over the same spectrum. However [9] stated that MU-MIMO only spreads capacity gains across multiple users, it does not basically change them. But for overall capacity across multiple users to increase using MU-MIMO, the base station must increase the number of antennas proportionally to the number of users in the cell. This is a big challenge for cellular base stations which often serve numerous users, the implication being that the number of antennas needed at a base station could become difficult to manage.

Furthermore, [14] added that in contrast to SU-MIMO, MU-MIMO networks are exposed to strong co-channel interference and in order to achieve high throughput and multiplexing gain, MU-MIMO systems require perfect Channel State Information (CSI). But SU-MIMO performs better at low SNRs, while MU-MIMO provides better performances at high SNRs. The comparison between MU-MIMO and SU-MIMO is summarized in table 1.

Table 1: Comparison between MU-MIMO and SU-MIMO systems [14]

Feature	MU-MIMO	SU-MIMO
Main aspect	Base Station communicates with multiple users	Base Station communicates with a single user
Purpose	MIMO capacity gain	Data rate increasing for single user
Advantage	Multiplexing gain	No interference
CSI	Perfect CSI is required	No CSI
Throughput	Higher throughput at high SNR	Higher throughput at low SNR

(c) Interference Management Technique

Interference in wireless networks may come from either a transmitter operating at the same channel at some distance away from another transmitter or interference can be as a result of signal leaks or spillovers from transmitters operating at adjacent channels. Since Shannon's law suggests that channel capacity depends on the signal bandwidth and on the strength of the signal relative to the noise and interference at the receiving equipment, it implies that any technique that mitigates or minimizes interference in wireless systems should increase the system capacity. One of such techniques is Coordinated Multi-Point Transmission and Reception (CoMP). CoMP has been employed in LTE-A and 4G cellular networks to improve spectral efficiency by leveraging on inter-cell interference. CoMP techniques utilize transmit and receive antennas from multiple antenna locations, which may not belong to the same physical cell, thus reducing inter-cell interference and improve system spectral efficiency [16], [17].

CoMP does not avoid inter-cell signal leakage, but leverages undesirable interfering signal from adjacent cells (or sectors) by allowing UEs to communicate simultaneously with several cells sites (or sector antennas at a single cell site). Due to the fact that CoMP coordinates the transmission, what was considered interference from adjacent cell sites or sector antennas is converted into useful information carrying bandwidth, thus ensuring reception of more signal. Up to date channel information and synchronization must be ensured by the control traffic. Thus, this requirement demands that a high capacity backhauls are needed to support CoMP cluster. This backhaul requirement limits CoMP from achieving a MIMO-like linear capacity increase [2], [9].

(d) Frequency Reuse

Frequency reuse is a technique that involves the reuse of frequencies and channels within a cellular system in order to improve spectral efficiency and system capacity. In cellular networks, users in different geographic areas or different cells use the same frequency simultaneously; this increases the capacity in a given area. Frequency reuse requires that frequencies allocated to an operator are reused in a repeating regular pattern of cells. This repeating regular pattern of cells is called 'cluster'. A 'cluster' is a set of different frequencies used in group of cells, as depicted in figure 1.

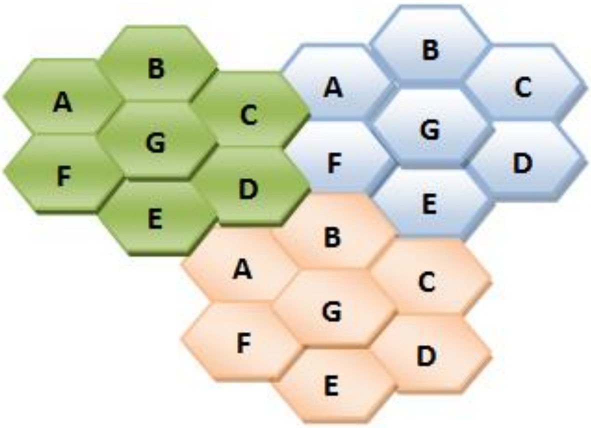

Figure 1: Mobile Cellular Frequency Reuse Illustration. Cells with same color represent clusters; Cells with the same letter use the same set of frequencies. Clusters are replicated over the coverage area.

Cells are designed to use frequencies only within its boundaries. This allows same frequencies to be reused in other cells in another cluster thus avoiding interference. Such cells are called co-channel cells. The author in [18], pointed out that the reuse of frequency in multiple locations of a large geographic area leads to considerations of interference from different areas (cells) that use the same frequency. Such interference is called co-channel interference. Co-channel interference can be approached by considering the following parameters [18], [19].

Let S_T be the total number of Radio Frequency (RF) Channels available for use in a cellular system, let C_C represents the allocated channels per cell reflecting the system capacity at a given location; and let K be the number of cells that is repeated to provide the coverage over large area. The three parameters are related by the following expression:

$$S_T = K.C_C \qquad (3)$$

The K cells which collectively use the complete available frequencies are called cluster, and the factor K is called the cluster size. If a cluster is replicated R times within the system, the total number of channels C_T is used to measure the capacity and is given as:

$$C_T = KRC_C = RS_T \qquad (4)$$

From (3), it is obvious that K plays a major role in capacity determination. It is a function of how much interference a base station can tolerate while maintaining a good Quality of Service (QoS). The frequency reuse factor of a cellular system is denoted as $1/K$, since each cell within a cluster is only assigned $1/K$ of the total available channels in the system [19]. In figure 1, K is 7, which gives the frequency reuse factor of this system as 1/7. The choice of K introduces a trade-off between network capacity and interference. Using higher frequency reuse factor lowers the capacity of the network, but widens the distance between cells with same frequency allocation which results in lower interference. Similarly, using lower frequency reuse factor increases the capacity of the network, but lessens the distance between cells with the same frequency allocation which results in higher interference.

Thus, co-channel interference can be minimized by physically separating the co-channel cells by a minimum distance to provide sufficient isolation due to propagation. But co-channel interference unlike thermal noise cannot be overcome by simply increasing the transmitted signal power (hence the SNR). The reason being that high signal power increases the interference to neighboring co-channel cells [19].

(e) Small Cells/Spatial Reuse – Cell Splitting

In traditional cellular mobile systems, large geographic area is divided into a series of small geographically contiguous coverage areas called cells. But spatial reuse can be increased by employing cells with much smaller coverage areas than what traditional cellular systems offer. These smaller cells are integrated into the bigger (macro) cellular network layout. Various smaller cells employed in cellular networks in recent years include femto-cells, pico-cells, and micro-cells. Compared to macro-cells, the small cells are short range, lower cost, low power cellular access points that support fewer users [20].

By dividing macro-cells into smaller cells, the number of cells serving a given area is increased; thereby increasing the amount of data a cellular network can carry [20]. But [2] pointed out that though deploying small cells improve wireless network capacity, the technique is expensive, as it requires deployment of extra towers, antennas, radios, base station equipment, as well as adding backhaul links back into mobile operator's core network. Though [9] stated that using small cells reduces interference, ensures frequency reuse, and thus increasing system capacity, the work by [2] stressed that there could be slow implementation of reuse techniques because approval may need to be obtained from regulatory bodies before deployment of new cells or adding new equipment in pre-existing sites.

Furthermore, continued decrease in cells sizes to enhance system capacity has a challenge of user mobility management and handover issues, resulting in overhead increase in from of control traffic. And introduction of more and more adjacent base stations will create problem of inter-cell interference [9]. The work by [20] added that in large scale deployment of small cells such as femto-cells, cell selection/reselection is an important issue that affects UE battery life and network signaling load.

(f) Cell Sectorisation

Transmitting with higher signal strength limits the SNR for adjacent cells due to increase in interference. Thus, instead of focusing on capacity increase using high signal strength, we can shift focus to techniques that minimize interference. Sectoring is a technique that employs directional antennas to minimize co-channel interference and thus increasing the system performance and capacity. In sectoring, the channels used in a particular cell are broken down into sectored groups and are used only within a particular sector. Using directional antennas ensures that signal power is transmitted in a single desired direction, and thus co-channel interference and the number of interfering co-channel cells are reduced. In sectoring, a cell is normally partitioned into three 120^0 sectors or 60^0 sectors. The amount of sectoring used controls the factor by which the co-channel interference is reduced [19]. For instance, when a cluster size is 7, for 120^0 sector, the co-channel cells is reduced from 6 to 2, and for 60^0 sector, sectoring reduces co-channel cells from 6 to 1.

Though sectoring increases SNR and hence system capacities by reducing co-channel interference, it has some drawbacks. Firstly, increasing the number of antennas at the base station will increase the cost of equipment. Secondly, the number of handoff will increase, since sectoring reduces the coverage area of a particular group of frequencies. Thirdly, sectoring decreases *trunking efficiency*, due to channel sectoring at the base station. According to the author in [19], *trunking efficiency* is a measure of the number of users which can be offered a particular Grade of Service (GOS) with a particular configuration of fixed channels. The work in [21] pointed out that in dynamic channel assignment, channels are assigned dynamically in accordance with user traffic, and hence it offers better *trunking efficiency* than fixed channel assignment method. But sectoring which aims to decrease co-channel interference will decrease *trunking efficiency*.

(g) Carrier Aggregation

In 4G systems which include the LTE-Advanced (LTE-A), one of distinct features standardized by Third Generation Partnership Project (3GPP) is Carrier Aggregation (CA). CA is a technology that allows two or more Component Carriers (CCs) to be aggregated in order to achieve or support wider transmission bandwidths. The aggregated carriers may be of same or different frequency bands (i.e. contiguous or non-contiguous CCs), providing maximum flexibility in utilizing the scare radio spectrum available to mobile operators. CA technology supports very high data rates (up to 1 Gbps) over wide frequency bandwidths, up to 100 MHz [22], [23], [24].

Thus by combining multiple CCs, CA helps to increase the bandwidth allocation to mobile UEs. In addition, by aggregation of contiguous and/or non- contiguous frequency bands, CA enables aggregation of licensed and unlicensed frequency spectrum, thus it utilizes unlicensed frequency bands, thereby increasing the effective bandwidth, which aids in extending coverage. This improves network efficiency and enhances user experience. Although CA comes with huge benefits, it only provides access or utilization of available spectrum, but does not directly increase capacity or supply of spectrum. In addition, the cost and complexity of equipment are increased, because extra devices or components such as multiplexers are needed at the transmit end to combine the CCs while at receive end RF filters are needed to separate the CCs [25], [10].

(h) Power Control

A key resource management in wireless systems is power control which is used to deal with inter and intra-cell interference. In LTE for instance, power control is utilized in uplink to maximize the received signal power while minimizing the effect of inter-cell interference. LTE uplink power control consists of open-loop and closed-loop components. In open-loop power control, the UE uses the parameters and the measurements obtained from signals sent by the base station to set the transmitting power, there is no feedback from the UE to the base station informing it of the power to be used for transmission. But in closed-loop power control, the UE receives feedback from the base station. The feedback is used to adjust the UE transmitting power.

Open-Loop Power Control makes use of Fractional Power Control (FPC). Thus by ignoring the Closed-Loop Correction factor $[f(\Delta_i)]$ and the Modulation Coding Scheme offset (δ_{msc}), it is shown that the UE transmitting power can be set according the fraction of path gain (PSD_{tx}) that the user has to compensate for, which is given in equation (5), [26], [27].

$$PSD_{tx} = P_0 + \alpha PL \quad (5)$$

Where, P_0 is the power to be contained in one resource block, α is the path loss compensation factor; PL is the downlink path loss estimate.

Thus PSD_{tx} varies for each UE according to the experienced path gain. The values of α varies between 0 and 1, and are used to compensate between full compensation ($\alpha = 1$, i.e. the conventional power control) and no power control ($\alpha = 0$). For $0 < \alpha < 1$, the PSD_{tx} depends on the path loss of user. Thus the PSD_{tx} of each user differs, and in this case only a fraction of the path loss is compensated to the user [26], [27].

The Open Loop Power Control results in less complexity and low signaling, but cannot compensate for channel variation for individual users. In addition, FPC of Open Loop improves channel capacity, reduces power consumption and enables trade-off between cell edge bit rate and cell capacity. Furthermore, in FPC, higher throughput can be achieved for cell center users through improvement in SINR, but this comes at the cost of decrease in power of the cell edge users. The implication is lower SINR for cell edge users which results in poor performance. On the other hand, the Closed-Loop Power Control compensates for interference and variations in channel conditions but it demands high signal overhead [27].

(i) Mobile Data Offload.

Mobile data offloading is the use of network techniques and complementary technologies to deliver data originally targeted for cellular networks. The aim is to reduce cellular network congestion, improve capacity, make better use of the available resources and reduce cost of service delivery. To support exploding wireless broadband demands, mobile operators need access to licensed spectrum that support new generation cellular networks as well as more unlicensed spectrum for small cell Wi-Fi. This is because the current limited spectrum will not support the mobile broadband needs of future [3]. The increase in data traffic on cellular networks demands the need for offloading of traffic to enhance system performance.

The key technologies that have emerged to solve traffic or data offloading include Wi-Fi, femto-cells and IP flow mobility [28]. Wi-Fi offloading is gaining more attention than the rest. One of the reasons is due to built-in Wi-Fi capabilities of smart-phones. Another reason is that it allows the shift of data traffic from expensive licensed spectrum to unlicensed spectrum (2.4GHz and 5 GHz). Currently, more than one-third of global mobile traffic is offloaded to Wi-Fi, and this expected to increase in coming years [29], [3], [28]. From forecast by [30], mobile offload will increase from 60% (10.7 exabytes/month) in 2016 to 63% (83.6 exabytes/month) by 2021 as depicted in fig. 2.

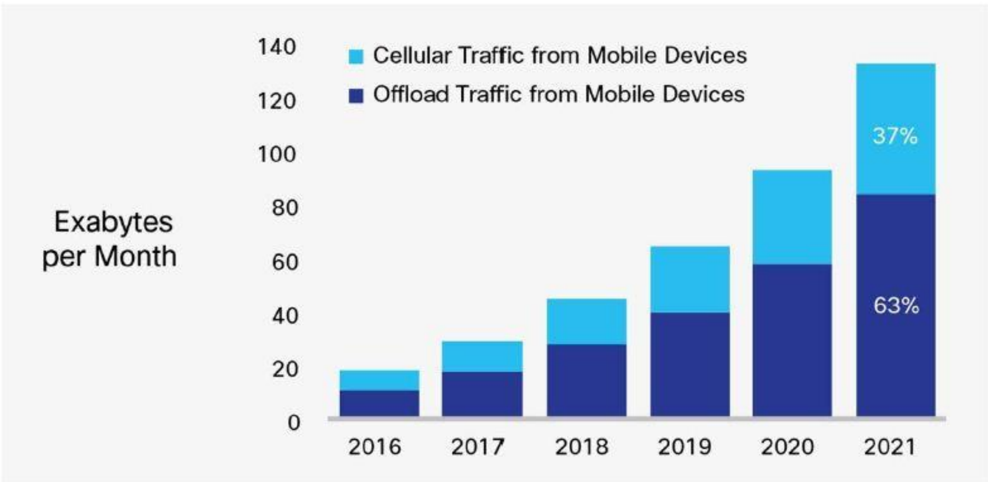

Figure 2: Forecast of Mobile Data Traffic Offload by 2021. The offload pertains to traffic from dual-mode devices (excluding laptops) over Wi-Fi or small-cell networks [30]

Though Wi-Fi has gained much attention than the other key data (or traffic) offloading technologies, much attention in recent times is being devoted to researches on Device to Device (D2D) communications in cellular networks as noted by [31]. In particular, the interest for D2D communications has been occasioned by the need to offload traffic from the cellular network in a given area. The aim is to effectively utilize the limited or the scarce network resources. D2D is very flexible and has the potential to offload traffic from the core network, thus reducing the overload density of the cellular system [32], [33].

Notwithstanding the benefits of mobile data offloading through technologies such as Wi-Fi, there are some drawbacks depending on the approach the mobile operator use to offload data unto a Wi-Fi network. One of the drawbacks is that the operator may lose visibility and control of its users when they are connected to Wi-Fi network. Another challenge is that the operator would not be able to deliver any subscribed service such as ring or caller tunes which leads to loss of revenue. Other challenges faced by mobile operators in Wi-Fi offloading include: where to offload, when to introduce offloading, backhaul challenges, availability and acquisition of site(s), deployment issues, regulatory constraints, security issues and charging method or policy to adopt [28], [29].

(j) Device to Device Communications

D2D communication allows devices to communicate directly without the assistance of base station. Thus D2D reduces latency, gives better throughput, improves link reliability between devices, enhances spectral/energy efficiency and hence system capacity. In addition, it has the potential to effectively offload traffic from the network core. It is considered as an essential component of the 5G networks [34].

D2D communication is categorized as *in-band* (when it utilizes the licensed spectrum) or *out-band* (when it uses the unlicensed spectrum – similar to WLAN and Bluetooth technologies). In-band D2D is further categorized as *underlay* and *overlay*. D2D underlay allows D2D links and cellular links to use the same spectrum. But in D2D overlay, dedicated portion of the available spectrum is reserved for D2D communication, while the remaining spectrum is used for cellular communication. Similarly, out-band D2D is categorized as either *autonomous* or *controlled*. In autonomous situation, the radio interfaces are managed and coordinated by the User Equipments (UEs) themselves. But in controlled category, the D2D radio interfaces are managed by the eNodeBs, i.e. base stations [35], [32].

Since in underlay, the D2D and cellular users use the same spectrum, in-band underlay achieves more spectral efficiency than the overlay. But the major issue with underlay D2D communication is interference that occurs between D2D and cellular users, which also affects the QoS and reliability of the two systems. On the other hand, the overlay D2D helps to reduce interference between the D2D and cellular users. Notwithstanding, mutual interference still exists between D2D users since multiple D2D users can reuse the same resource blocks in overlay. This affects the overall throughput of the network [36], [37].

Out-band D2D major aim is the elimination of interference between D2D and cellular users, but the utilization of the unmanaged unlicensed spectrum (in the presence of technologies such as Wi-Fi) puts no guaranty on the network QoS and introduces some level of interference according to [38]. But the work by [36] added that D2D transmission security is affected in such scenario and coordinating operation in two different bands using independent radio interfaces introduces the problem of critical power management.

The aim of network assisted or controlled out-band D2D category is efficient and effective management of D2D communications and at the same time provision of cellular communications QoS requirements thus improving the overall throughput of the system. But the management of D2D activities introduces large signaling overhead. On the other hand, autonomous out-band D2D has the advantage of less signaling overhead; hence it can offer better service to cellular users. But the drawbacks include high implementation complexity and the need to manage interference among D2D users [36].

In addition to the drawbacks and issues that hamper the implementation of D2D communications discussed above, there are other issues that need to be addressed while deploying D2D communications in wireless systems. Such issues include peer discovery, mode selection, resource allocation, security issues, power control and mobility management [32], [35], [39], [40].

The challenges of bandwidth and power limitations in wireless systems and the methods or techniques adopted to tackle the challenges are summarized in table 2.

Table 2: Summary of Methods and Techniques Employed to Increase Wireless Capacity

S/N	Approaches/Techniques	Aims/Strengths	Challenges
[A] Considerations from Shannon's Law			
1.)	Increase of bandwidth	Proportionate increase in channel capacity.	Increase of noise power.
2.)	Increasing signal power	Aims to increase the SNR, and hence the capacity.	(a) Increase of adjacent channel interference, thus lowering of SNR. (b) Depletion of device battery life. (c) Transmitted power is sometimes constrained by regulations,.
[B] Various Techniques to Increase Wireless Capacity			
1.)	Spectrum Regulations/or re-allocation	Aim is to have proper management of the spectrum	(a) Only a fraction of the spectrum is available for provision of cellular wireless access. (b) Re-allocation of spectrum is unlikely given that the stakeholders have divergent interests.
2.)	Antenna (MIMO) Techniques	(a) Improves capacity without increase in transmission power. (b) MU-MIMO aims to achieve high throughput, performance and multiplexing gain.	(a) Increase of base station antennas results in high cost and complexity. (b) Higher order MIMO in UE increases UE size and power consumption. (c) MU-MIMO networks are exposed to co-channel interference, and require perfect Channel State Information (CSI).
3.)	Interference Technique (CoMP)	CoMP reduces inter-cell interference and improves spectral efficiency	Requires up to date channel information and synchronization, and hence high capacity backhauls
4.)	Frequency Reuse	Improves spectral efficiency and system capacity.	Higher frequency reuse factor lowers the capacity but reduces interference. Lower frequency reuse factor increases capacity but gives higher interference.
5.)	Cell Splitting	Improves wireless capacity by increasing the amount of cellular data, reduces interference and ensures frequency reuse.	(a) Deployment of extra towers, antennas, etc makes it an expensive technique. (b) Has a challenge of user mobility management and handover issues. (c) Increase in control traffic overhead and network signaling load. (d) Creates problem of inter-cell interference. (e) Cell selection/reselection affects UE battery life.
6.)	Cell Sectorisation	Minimizes co-channel interference and hence increasing system performance and capacity.	Increase in the cost of equipment, increase in number of handover and decrease in trunking efficiency.
7.)	Carrier Aggregation	Supports wider transmission bandwidths/or utilization of available spectrum, improves network efficiency and enhances user experience.	(a) Does not directly increase capacity or supply of spectrum. (b) The cost and complexity of equipment are increased.
8.)	Power Control (for LTE/LTE-A)	(a) Deals with inter and intra-cell interference. (b) Open Loop Power Control has less complexity and low signaling. (c) FPC of Open Loop improves throughput for cell center users (d) Closed-Loop Power Control compensates for interference and variations in channel conditions.	(a) Open Loop Power Control cannot compensate for channel variation for individual users. (b) FPC of Open Loop introduces decrease in power of the cell edge users. (c) Closed-Loop Power Control demands high signal overhead.
9.)	Mobile Data/Traffic Offload	Reduces cellular network congestion, improves capacity, makes better use of the available resources and reduces cost of service delivery.	(a) The operator may lose visibility and control of its users. (b) May lead to loss of revenue from any subscribed service such as ring or caller tunes. (c) There are issues such as backhaul challenges, security and charging method or policy to adopt.
10.)	Device to Device (D2D) Communications	Reduces latency, improves throughput, improves link reliability between devices, and enhances spectral/energy efficiency.	(a) Interference occurs between D2D and cellular users in underlay D2D communication. (b) Mutual interference still exists between D2D users in overlay D2D. (c) Utilization of the unmanaged unlicensed spectrum in Out-band D2D affects the network QoS and poses security threats. (d) Controlled out-band D2D introduces large signaling overhead while autonomous out-band D2D introduces high implementation complexity and interference among D2D users. (e) Other challenges of D2D communications include: peer discovery, mode selection, resource allocation, mobility management.

IV. Conclusion

There has been high demand for connectivity availability in wireless networks due to increase in number of users and mobile devices. The consequence is striking increase in the consumption of bandwidth and power which are the major resources that influence the wireless channel capacity. These major resources that influence wireless channel capacity are limited due to government regulations of the transmission bandwidth and the low powered devices used in wireless communications. In this paper we have discussed various methods and techniques that have been adopted to increase wireless channel capacity. These methods or techniques all seek to increase or enhance either the transmission bandwidth or the signal power. Though the methods or techniques can offer significance increase or improvement in channel capacity, each has its challenges or limitations.

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