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Heterogeneities of Wireless Networks: Radio Resource Management Challenges and Possible Solutions

Olabisi E. Falowo[1]

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Abstract This paper examines the heterogeneities of wireless networks from six different perspectives, namely mobile terminals, radio access technologies (RATs), network services, users, network operators, and network geographical areas. These different aspects of wireless network heterogeneities offer certain benefits but also pose some challenges to effective management of radio resources. The challenges of wireless network heterogeneities are highlighted in this paper and possible solutions are proffered. The paper then compares recent network selection algorithms proposed for wireless networks with respect to the aspects of heterogeneities considered. Comparative analysis of the different network-selection algorithm shows that whereas RAT, services, and users heterogeneities have received much attention in the literature, terminal, operator, and geographical area heterogeneities have not been widely considered. Thus, more attention should be given terminal, operator, and geographical area aspects of wireless network heterogeneities so that the problems of radio resource management in wireless networks can be addressed in a more holistic way. An algorithm that considers the different aspects of network heterogeneities is proposed, and simulation results are given to highlight the effects of network heterogeneities on connection-level quality of service provisioning in heterogeneous wireless networks.

Keywords Wireless networks · Network heterogeneity · Mobile terminals · Radio access technology · User · Operator

1 Introduction

Current wireless networks encompass different types of users accessing distinct network services through mobile devices of different capabilities connected to diverse radio access technologies (RATs) deployed by different network operators in diverse geographical

✉ Olabisi E. Falowo
bisi@ieee.org

[1] Department of Electrical Engineering, University of Cape Town, Rondebosch, South Africa

areas. Thus current wireless networks are heterogeneous from different perspectives namely mobile terminals, radio access technologies, network services, network users, network operators, and network geographical areas. Figure 1 shows the different aspects of heterogeneities of wireless networks.

In the literature, heterogeneities of wireless networks have mostly been treated with regard to RATs, network services, and users [1–6], whereas mobile terminal, operator, and geographical area heterogeneities have not received due attention. However, the different aspects of wireless network heterogeneities offer certain benefits, but also pose some challenges to effective management of radio resources in the networks. Therefore, this paper presents a comprehensive view of wireless network heterogeneities from the six different perspectives mentioned above.

In existing wireless networks, mobile terminals have different capabilities with respect to terminal screen features, terminal modality, homing ability, terminal portability/weight, services supported, battery features, data input method, data storage capacity, processor speed, and operating system. RATs have different complimentary features with respect to services supported, cell size, cell capacity, operating frequency, network security level, service cost, delay and jitter, modulation techniques, multi-access techniques, and duplex techniques. Services provides by wireless networks have heterogeneous features with regard to service class, service type, bandwidth requirement, service adaptability, symmetry, time-sensitivity, and packet-loss tolerance. Network users differ with respect to class of services demanded, quality of service requirements, willingness to pay, mobility pattern, device capability, time-of-use pattern, service security requirements, service consumption, and technology awareness. Operators of wireless networks have different features with regard to scale of network deployed, number of RATs deployed, ownership of network infrastructure, types of services provided, pricing strategy employed, and level of collaboration. Wireless networks are deployed in diverse geographical areas, which are characterized by population density, geographic position, topography, infrastructure availability, legislature and spectrum availability, and proneness to disaster and sabotage. These different aspects of wireless network heterogeneities are discussed in details in the subsequent sections.

In wireless networks with multiple RATs, a number of joint radio resource management (JRRM) algorithms have been proposed for efficient management of radio resources [7–10]. These JRRM algorithms are designed for making network selection decisions, packet scheduling, power control, handover decisions, bandwidth allocation, etc. The overall objectives of JRRM algorithms are to enhance radio resource utilization, improve quality of service, ensure overall stability of network, enhancement of users' satisfaction, and increase in operators' revenue [7, 8]. This paper focuses on challenges of network

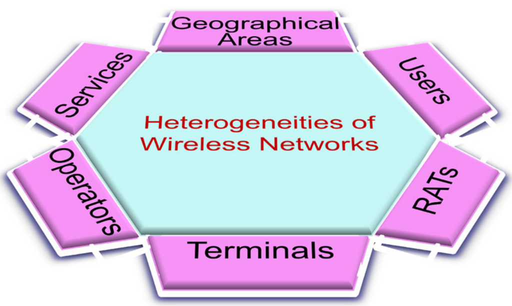


Fig. 1 Heterogeneities of wireless networks

heterogeneities on radio resource management in wireless networks, in general, but pays particular attention to network-selection algorithm, which is one of the JRRM algorithms.

The contributions of this paper are twofold. First is the qualitative analysis of the challenges of the different aspects of wireless network heterogeneities from six different perspectives. The second contribution is the comparative analysis of recent network-selection algorithms with respect to the aspects on wireless network heterogeneities considered.

The rest of this paper is organized as follows. Section 2 discusses mobile terminal heterogeneity. Section 3 focuses on RAT heterogeneity. Section 4 analyses network service heterogeneity. Section 5 discusses users' heterogeneity. Section 6 focuses on operator heterogeneity and Sect. 7 describes geographical area heterogeneity. Section 8 compares the recent network-selection algorithms proposed for heterogeneous wireless networks with respect to the aspects of wireless network heterogeneities considered. In Sect. 9, an algorithm that considers the different aspects of network heterogeneities is proposed, and Sect. 10 concludes the paper.

2 Mobile Terminal Heterogeneity

A user's mobile terminal is what grants the user connectivity to an operator's network. Existing wireless networks support diverse types of mobile terminals, such as mobile phones, tablets, phablets, personal digital assistants, and laptops, which have a wide range of capabilities [11–16]. As mobile networks evolve from one generation to another, equipment manufacturers have come up with different terminals that have increasing capabilities in order to take full advantage of new radio access technologies as well as the existing ones in heterogeneous wireless networks. Moreover, advancement in electronic technologies has led to development of mobile terminals that have higher capabilities. Consequently, mobile terminals of various capabilities coexist in wireless networks, and a combination of these terminals with different capabilities is referred to as heterogeneous mobile terminals. Figure 2 illustrates the different aspects of mobile terminal heterogeneity.

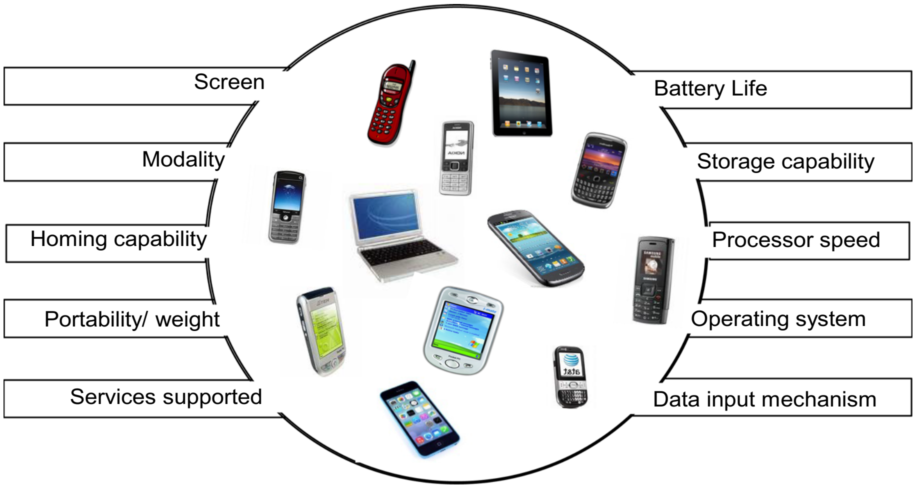


Fig. 2 Illustration of mobile terminal heterogeneity

The heterogeneity of mobile terminal in wireless networks can be analyzed from different perspectives. In this paper, mobile terminal heterogeneity is analyzed from ten perspectives shown in Fig. 2, considering ten important key features namely: screen features, modality, homing capability, portability/weight, supported service, battery features, data storage capability, processor speed, operating system, and data input method. These features are discussed in Table 1.

Some aspects of mobile terminal heterogeneity have been studied in the literature. In [14], the effect of terminal heterogeneities in heterogeneous wireless network has been studied. In, [23] effect of terminal homing capabilities has been studied. In [20], the effect of mobile phone screen size on video based learning quality of experience has been has been studied.

3 RAT Heterogeneity

Current wireless networks consist of terrestrial RATs such as WLAN, UMTS, CDMA2000, LTE, etc., and non-terrestrial networks such as satellite and high-altitude balloon networks. RAT heterogeneity refers to diversities in the features of different RATs coexisting in the same geographical area. The demand for higher data rates, improved coverage, enhanced quality of service, reduced transmitted power, and cost effectiveness have led to the deployment of multiple RATs in the same geographical area. These different RATs have complementary features that are advantageous when radio resources are jointly managed [24]. For example, WLANs have high data rates, low coverage, low cost, and low security level whereas 3G networks have higher coverage, higher security, and lower data rate than WLAN. Satellite network has wide coverage, high cost, high delay (resulting from long round trip time), and low data rate, poor coverage indoor, which makes them less suitable for real-time communication [25]. RAT heterogeneity enables joint management of radio resource of different networks for enhanced QoS provisioning, better radio resource utilization, and cost effectiveness. Figure 3 illustrates aspects of RAT heterogeneity in wireless networks.

RAT heterogeneity in wireless networks can be analyzed from different angles. In this paper, RAT heterogeneity is analyzed from nine perspectives shown in Fig. 3. The nine perspectives are services supported, cell size, cell capacity, operating frequency, security level, service cost, delay and jitter, modulation techniques, multiple access technique, and duplex technique. RAT heterogeneity is discussed in Table 2.

4 Service Heterogeneity

Service provisioning is the primary reason for deploying wireless networks, and there are various services provided to users by wireless networks. These services, which include voice call, audio streaming, audio conferencing, video call, video streaming, web access, email, file transfer, remote login, online banking, presence, and navigation, etc., can broadly be classified as voice, data, and video. The aspects of service heterogeneity considered in this paper are service class, service type, service adaptability, bandwidth requirements, service symmetry, time-sensitivity, and packet loss tolerance. Figure 4 illustrates aspects of service heterogeneity while Table 3 contains analysis of service heterogeneity.

Table 1 Mobile terminal heterogeneity

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Screen features	Screen is an important interface between a user and a mobile device, with the ability to present information in terms of text, graphics, animation, and video [17]. Important screen features are screen size, screen density, orientation, resolution, and number of screens per device	Mobile terminal screens are classified in different ways based on screen size, screen density (pixel density), screen orientation (horizontal, vertical, or both), screen resolution, and number of screen per device (single screen or multiple screens)	The screen technology is critical to saving battery power [17]. As screen resolution becomes higher and screen size becomes bigger, the power consumption increases [18]. Moreover, as the required resolution increases, the need for pixel information dramatically increases, and the bandwidth required for video transmission increases [19]. Mobile terminal screen size affects a user's quality of experience on video [20]	It is important to consider screen size in allocation of radio resources for video calls. Video can be coded in layers or at different rates. More layers/higher data rates are required for big screens whereas fewer layers/low data rates are required for small screens in order to maintain the same video quality. Use of energy saving algorithms can reduce energy consumption of mobile terminals' screens [21]
Modality	Modality refers to the number of network interfaces a mobile terminal has, which determines the RAT to which the terminal can be connected	Mobile terminals are classified as single-mode, dual-mode, triple-mode, quad-mode, and so on	Terminals with low modality will experience a higher call blocking/dropping probability whereas terminals with high modality will experience a lower call blocking/dropping probability than terminals with low modality [14]	It is important to consider terminal modality in making RAT-selection decisions by allocating terminals with high modality to RATs with low terminal-support index. Moreover, the use of terminals with high modality by subscribers will improve connection-level quality of service and overall radio resource utilization [14]
Homing capability	Homing capability refers to the number of RATs to which a mobile terminal can be connected simultaneously	Mobile terminals are classified as single-homed, dual-homed, triple-homed, and so on	Terminals with high homing capability allow more flexibility in allocation of radio resources thereby enhances radio resource utilization and reduce call blocking/dropping probability. Moreover high-homing capability enhances communication reliability, bandwidth aggregation, and load balancing [15]	Quality of service, load balancing, and radio resource utilization can be improved by delivering high-bandwidth consuming calls such as high-definition video to multi-mode terminals having multi-homing capability through multiple RATs

Table 1 continued

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Portability/weight	Portability refers to the size and weight of a mobile terminal	Mobile terminals are classified based on their physical dimensions	In the design of mobile terminals, size is one of the most important constraints. Small mobile terminals are easy to carry around but have less battery space, screen size, etc. Thus smaller mobile terminals can easily run out of energy than bigger ones	Tradeoff between mobile terminal's weight and battery capacity depends on individual's need
Service supported	Class of services supported by a mobile terminal	Services supported by a mobile terminal can be classified as single service or multiple services. Single-service terminals support only one class of service such as voice only or data only. Multiple-service terminals support multiple services such as voice, data, and video	Services supported by mobile terminals determine the amount of radio resources consumed by the devices. Terminals that support video calls require more bandwidth than terminals that support voice calls	Adaptive services such as video call can be delivered to users at different rates based on bandwidth availability and quality of services requirement of individual users
Battery capacity	Battery capacity is the total Amp-hours available when the battery is discharged at a certain discharge current from 100 percent state-of-charge to the cut-off voltage [22]	Battery capacity of a mobile terminal can be classified using fuzzy (linguistic) terms such as very high, high, medium, low, and very low	Battery capacity affects talk time and frequency of battery recharge. Low battery capacity increases the frequency of battery recharge. Ageing of a battery also results in decrease in the battery's capacity over its life	Increase in energy density of mobile terminals will increase talk time and reduce the frequency of battery recharge
Storage capability	Amount of data, for example, in gigabytes, that can be stored on a mobile terminal	Storage capability of a mobile terminal can be classified using fuzzy linguistic terms such as very high, high, medium, low, and very low	Storage capability affects storing and sharing of multimedia contents such as videos and photos, and consequently affects service consumption rate of users	The use of memory cards and cloud storage will enhance storage capability of mobile terminals

Table 1 continued

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Processor speed	The processor is the brain of a mobile terminal and the speed of a mobile terminal's processor is measured in megahertz or gigahertz	The speed of a mobile terminal processor can be classified using fuzzy (linguistic) terms such as very high, high, medium, low, and very low	A mobile terminal processor's speed will affect a user's quality of experience. A high processor speed can provide quicker multitasking, faster Web browsing, smoother game play, and better battery life	Higher processor speed will enhance users' quality of experience
Operating system	A mobile terminal operating system is software that manages the terminal and allows it to run applications	Various operating systems such as Android, iOS, Windows, Firefox, Symbian, Tizen, and MontaVista Linux are used in mobile terminals. These operating systems can be classified as open source or closed source	Operating system of a mobile terminal affects its usability, energy management efficiency, robustness	Mobile terminal usability, energy management efficiency, robustness should be considered in development of a new operating system or enhancement of existing operating system for mobile terminals
Voice, video, and data input method	These are the mechanisms such as Qwerty keyboard, touch screen, voice recognition, microphone, and video camera used to input information into a mobile terminal	Input mechanism can be classified voice-centric, video-centric, or data-centric	It affects usability of a mobile terminal, and the rate of service consumption	Users' friendliness is an important factor to be considered in the design of input mechanisms for mobile terminals because it affects service consumption rate

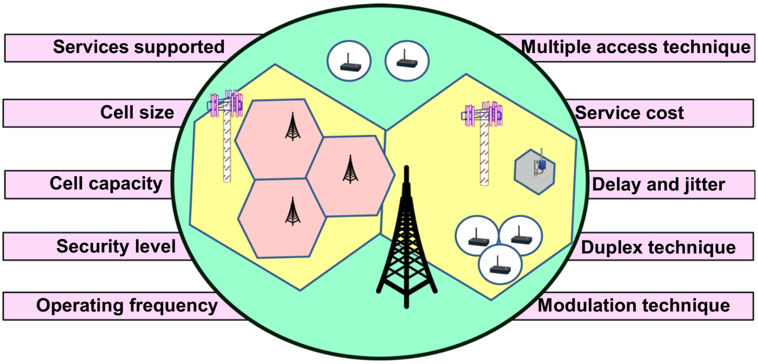


Fig. 3 Illustration of RAT heterogeneity

5 Users' Heterogeneity

It was projected by the International Telecommunication Union (ITU) that mobile-cellular subscriptions would reach almost 7 billion by end 2014 and that the number of mobile-broadband subscriptions will reach 2.3 billion globally, with 55 % of them in developing countries [29]. Thus, the penetration of mobile network has increased dramatically in recent years to accommodate users from all walks of life. Consequently, wireless network users are quite diverse with respect to class of network service(s) demanded, QoS requirements, willingness to pay, mobility pattern, device capability, time-of-use pattern, security requirement, service consumption, and awareness of technology. The knowledge of users' heterogeneity is important for network planning and optimization. Moreover, the different aspects of users' heterogeneity could be exploited for efficient radio resource management in wireless networks, which involves managing the allocation of radio resources to different users in order to maximize the number of services delivered while ensuring user satisfaction [30, 31]. Figure 5 illustrates the different aspects of users' heterogeneity in wireless networks.

The analysis of users' heterogeneity in wireless networks is presented in Table 4.

6 Operators' Heterogeneity

Network operators provide telecommunication services, and can be classified in a number of ways. In this paper, network operators' heterogeneity is analyzed from six different perspectives namely: scale of network, number of RATs deployed, ownership of network infrastructure, pricing strategies, services provided, and level of collaboration.

Based on the scale of network, network operators can be classified as local, regional, national, or international. Local network operators are the lowest category of operators. Their frequency spectrum is licensed for use within a local area making the services provided to subscribers limited to a particular location. In the second category, regional network operators are given spectrum licenses to operate with a certain region or province. In the third category, national network operators have spectrum licenses to operate within a country, and in the fourth category, international network operators have spectrum licenses to operate within multiple countries. Network operators can also be classified based on the number of networks deployed as single-RAT or multi-RAT operator. Single-RAT network

Table 2 RAT heterogeneity

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Services supported	Class of services supported by a RAT	Network services can be broadly classified as voice, video, or data	Different RATs are optimized for different services	It is important to consider service class in make network-selection decisions in wireless networks
Cell size	Geographical area covered by each cell	Cell size can be classified as Mega cell, Macro cell, Micro cell, Pico cell, or Femto cell	Smaller cells have a higher capacity than bigger cells. However, smaller cells incur high frequency of handoffs. Bigger cells require high transmission power from mobile terminals	Slow-moving mobile terminals requiring high data rate can be assigned to smaller cells whereas fast-moving mobile terminals can been assigned to bigger cells
Cell capacity	Entire data rate of the air interface of a RAT or the number of voice calls that can be supported on the air interface, assuming that the data rate of a voice call is fixed	Network capacity can be classified as soft or hard. Capacity can also be classified using linguistic terms such as: high, medium or low	Cell capacity determines the maximum number of voice calls or the maximum data rate a cell can support. High capacity RAT can support more voice calls and high data rates and enhance quality of service	Cell capacity can be enhanced by adding more carriers, cell splitting, cell sectoring, frequency borrowing, deployment of small cells within macro cells, and joint management of radio resources among cells of different RATs
Operating frequenc	This is the range of radio frequency used by a RAT. Different RATs operate at different frequencies, and may have a particular frequency reuse pattern	Frequency can be classified as licensed or unlicensed. Frequency can also be classified based on frequency bands	There is possibility of interference from other users in unlicensed spectrum band, which may degrade the QoS experienced by the users. On the other hand, RATs operating in the licenced bands have better QoS but incur higher cost	The use of dynamic spectrum management will improve the efficiency of utilization of frequency spectrum
Network security level	This is a measure of the provisions and policies adopted in the network to prevent and monitor unauthorized access, misuse, modification, or denial of access to network resources [26]	RAT security level can be classified using linguistic terms such as: very low, low, average, high, very high	RAT security level affects users' preferences for a particular RAT, and utilization of network resources for specific services	It is important to enhance network security level of individual RAT in a heterogeneous wireless network

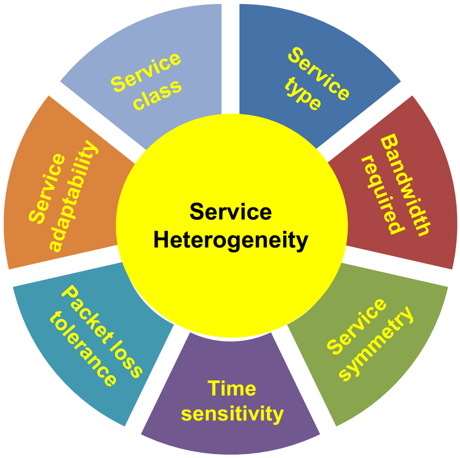
Table 2 continued

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Service cost	This is the amount of money charged for network services	Service costs can be classified as fixed or dynamic. They can also be classified using fuzzy linguistic variables such as low, average, and high	Users are price-sensitive. Service cost affects service consumption rate and the utilization of radio resources of RATs	Service cost can be used to control congestion in wireless networks by increasing the price when network is congested and reducing price when the network is underutilized. It can also be used to control congestion among multiple RATs by increasing the cost in congested RATs and decreasing cost in underutilized RATs
Delay and jitter	Delay is the time taken to transmit a packet, while jitter is variation in delay	There are different types of delay in RAT such as handover delay, transmission delay, etc.	Delay and jitter affect users' quality of service	Joint management of radio resources among multiple RATs will enhance overall quality of service
Modulation technique	These are the techniques for varying a modulating wave with one or more parameters of a carrier wave	Digital modulation techniques can be classified based on the characteristics of the carrier wave used in the modulation. Examples modulation techniques are Amplitude Shift Keying, Frequency Shift Keying, Phase Shift Keying, Quadrature Amplitude modulation, etc.	Modulation techniques determine the efficiency of radio resource utilization	Increase in efficiency of modulation schemes and joint management of radio resources among multiple RATs will enhance overall radio resource utilization
Multiple access techniques	These are protocols for allocating network resources among multiple users	Multiple access techniques can be classified as contention-based (e.g. CSMA/CA used in WLAN) or conflict-free (e.g. TDMA used 2G, CDMA used 3G, and OFDMA used in 4G networks)	The multiple access technique used determines the efficiency of radio resource utilization	Joint management of radio resources among multiple RATs will enhance overall radio resource utilization

Table 2 continued

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Duplex technique	These are techniques used for two-way communications: the uplink and the downlink	RAT duplexing techniques can be classified as frequency division duplex (FDD), time division duplexing (TDD), code division duplexing (CDD), space division duplexing (SDD), polarization division duplexing (PDD), and hybrid division duplexing (HDD) [27]	A RAT duplexing technique affects the flexibility in allocation of radio resources in uplink and downlink directions for different services. For example TDD is more flexible that the FDD	It is important to give a higher priority in assigning symmetric services to non-flexible RATs (e.g. RAT with FDD) and give priority to assigning asymmetric services to flexible RATs (e.g. TDD) [27]

Fig. 4 Illustration of service heterogeneity



operators deploy only one type of RAT such as IEEE802.11 WLAN whereas multiple-RAT network operators deploy multiple RATs such as WLAN and UMTS network, GPRS and UMTS and LTE, etc.

Moreover, based on ownership of network, network operators can be classified as licensed network operators or virtual network operators. A licensed network operator owns or controls all the equipment necessary to provide network services to subscribers, including the radio frequency, radio access network, and the core network. On the other hand, virtual network operators provide network services directly to their subscribers, and they do not own the network infrastructure or the frequency licenses but lease them from licensed network operators. Virtual network operators promote competition among operators [33].

Considering pricing strategies, network operators employ a variety of pricing mechanisms, which can be broadly classified as prepaid, postpaid, or hybrid. Pricing schemes can also be classified as fixed or dynamic. In prepaid pricing scheme, credit is purchased in advance by the network user through a variety of payment methods. The purchased credit is then used to pay for services consumed by the mobile terminal of the user. If there is no available credit then access to the requested service is denied. In postpaid pricing scheme, there is a contractual arrangement between the user of the mobile terminal and the network operator. The contract may be long term or short term, and payments for services consumed by the user are made at agreed periods of time. Furthermore, based on services provided, operators can be classified as single-service or multiple-service network operators. Single-service network operators provides mainly a single type of service such as voice only or data only whereas multiple-service network operators provide multiple services such as voice, data, and videos services simultaneously.

Network operators can also be classified based on the level of operator collaboration among them, which can be: ‘no sharing’ (no collaboration), passive infrastructure sharing, access network sharing, core network sharing, frequency spectrum sharing, and roaming-based sharing. [34–36]. In ‘no sharing’, a network operator does not share network resources with other operators. This has some disadvantages because sharing of network infrastructure among network operators reduces infrastructure cost and also provides a better coverage of network service for network users. In passive infrastructure sharing, physical resources such as network sites, power equipment, transmission equipment, network cabinet, and network tower for antenna placement are shared among operators. In

Table 3 Services heterogeneity

Heterogeneous features	Explanation	Classification	Effect on radio resource management/ quality of service	Potential solution
Service class	This refers to the class of calls made by users	Service class can be broadly categorized as voice, video, and data	Different class of service has different QoS requirements	It is important to consider service class in allocation of services to RATs. Service class differentiation can be adapted to meet different user's needs
Service type	This refers to whether a call is newly initiated in a cell or handover from a neighboring cell	Service types can be classified as new call or handoff call	Dropping a handoff call is more annoying to a user than blocking a new call. Thus, handoff calls have a higher priority over new calls, and therefore affects reservation of radio resources in each cell of wireless network	It is important to prioritize handoff calls over new calls. Some radio resources are reserved for handoff calls
Adaptability/ Elasticity	Adaptability is the ability of a service to adjust to variation in available data rate without variation in service time while elasticity is the ability of adapt to variation in available bandwidth with simultaneous variation in service time [28]	Services can be classified as adaptive/or non-adaptive. Services can also be classified as elastic or non-elastic	Service adaptability/elasticity determines the flexibility in the amount of radio resources that can be allocated to individual calls	During the peak periods, adaptive/ elastic services can be downgraded to minimum acceptable bandwidth in order to free some radio resources to support new and handoff calls. Service adaptability enables delivering of video streaming at different data rates over a wide range of mobile terminals connected to diverse networks
Bandwidth requirement	The data rate required to support a service	Bandwidth can be classified using linguistic terms such as low, medium, or high	It affects the quality of service, and determines the total number of calls that can be supported by a base station or access point	Joint management of radio resources among multiple RATs will enhance overall radio resource utilization
Symmetry	Equality in the proportion data rates required to support a service in uplink and downlink directions	Services can be classified as symmetric or asymmetric	Service symmetry affects the utilization of radio resources in uplink and downlink directions	Giving priority in assigning symmetric services to non-flexible RATs (e.g. RATs using FDD) and giving priority in assigning asymmetric services to flexible RATs (e.g. RATs using TDD or CDD) will improve overall radio resource utilization

Table 3 continued

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Time-sensitivity	This is the delay/jitter tolerance of a service	Services can be classified as real-time or non-real-time service	Delay and jitter affect quality of service	It is importance to give a higher priority to real-time services in order to keep delay and jitter within acceptable limits
Packet-loss tolerance	This is the amount of packet loss a service can tolerate	Services can be classified as loss tolerant or loss intolerant	Packet-loss affects quality of service	Congestion control protocols are used to reduce packet loss in wireless networks

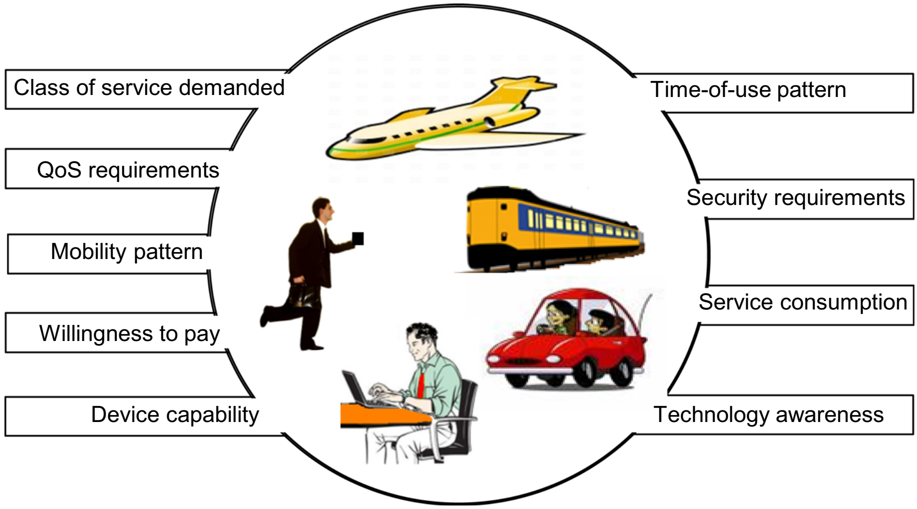


Fig. 5 Illustration of users' heterogeneity

access network sharing, access network equipment such as Node B, radio access technologies (RATs), and radio network controller (RNC) are shared among network operators [37]. In core network sharing, core network infrastructures are shared among network operators. In frequency sharing, licensed frequency bands are shared among network operators. Sharing of radio spectrum among operators improves the efficiency of spectrum utilization [38]. Roaming-based sharing is another form sharing among network operators [35]. It allows network operators to cover different regions/countries and thereby enables national/international roaming for the purpose of network coverage. In roaming-based sharing, network operators allow their subscribers to gain access to other network operators' radio resource for service continuity in regions/countries where their home operator's networks are nonexistent. Figure 6 illustrates the six aspects of operators heterogeneity considered in this paper, and Table 5 summarizes the different aspects of operators' heterogeneity.

7 Geographical Area Heterogeneity

Geographical area heterogeneity explains how the differences between geographical regions impact radio resource management in wireless networks. The aspects of geographical area heterogeneity considered in this paper are population density, geographic location, topography, infrastructure availability, legislature and spectrum availability, proneness to disaster and sabotage. Figure 7 illustrates the different area of geographical area heterogeneity.

Population density of wireless network users in a particular area affects the utilization of radio resources in the area. Based on population density, geographical area can be classified as urban, sub-urban, or rural areas. In an area of low population density, wireless networks will require less radio resources than in an area of high population densities. Thus, high-density areas are usually covered by multiple RATs with smaller cells in order to provide sufficient capacity for the users. Consequently, handoff frequency is higher in areas with high population density. High handover frequency is one of the challenges of

Table 4 Users heterogeneity

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Class of service demanded	Class of service(s) demanded by a user	Services demanded can be broadly classified as voice, data, and video	Different class of service requires different among of radio resources	A specific service can be delivered through the most suitable RAT(s) for the class of service
QoS requirements	Level of quality of service subscribed to by a user	Describes QoS currently required by a user for a specific service	QoS requirements of individual users affect the number of simultaneous calls that can be supported at the same time	QoS can be enhanced through joint management of radio resources in wireless networks. Service class differentiation can be adapted to meet different user's needs
Willingness to pay	Maximum amount of money a user is willing to pay for a service	Willingness-to-pay can be classified using linguistic terms such as low, medium, or high	Willingness to pay affects the amount of service(s) consumed by users	It is important to consider users' willingness to pay in fixing service prices, and in congestion control using dynamic pricing
Mobility pattern	This refers to speed, direction, and frequency of movement of subscribers in a wireless network	Users can be classified as Indoor, pedestrian, or vehicular users, based on their mobility pattern	Determines handoff rate, which affects allocation/reservation of radio resources in each cell of a wireless network	It is important to consider users' mobility pattern in making RAT-selection decisions and in allocation and reservation of radio resources in wireless networks
Device capability	This is the capability of the device owned by a user	Device capability can be classified using linguistic terms such as very low, low medium, high or very high	A user's device capability affects the connection-level QoS and the packet-level QoS experience by the user. It also affects the amount of services consumed by the user	Users can be incentivized to use mobile terminals with high capability by providing subsidies on the terminals or through contracts, where mobile terminal are given to users by network operators
Time-of-use pattern	Time at which a user regularly uses services	Time-of-use pattern can be classified as peak period or off-peak period	It results in variation of radio resources demanded by users throughout the day	Dynamic pricing can be used to incentivize/discentivize users during the off-peak/peak period respectively
Security requirement	This is the level of security required by a user	Security requirements can be classified using linguistic terms such as low, medium, or high	Level of security depends on the security features of available RATs	Individual user's security requirement should be considered in making RAT selection decisions

Table 4 continued

Heterogeneous features	Explanation	Classification	Effect on radio resource management/quality of service	Potential solution
Service consumption	Rate and amount of service used by users	Security consumption can be classified using linguistic terms such heavy, moderate and light [32]	Service consumption of individual users determines the utilization of radio resources	Joint management of radio resources will ensure load balancing and efficient allocation of resources to individual users
Technology awareness	User's knowledge and ability to use network services	Technology awareness of a user can be classified using linguistic terms such as low, medium, or high	Level of users' technology awareness affects service penetration and service consumption rate, which in turn affects utilization of radio resources in wireless networks	Service promotion and technology awareness campaign can improve the level of a user's awareness

RRM in an area of high user density. Frequent handovers (especially vertical handovers) drain the battery of a mobile device at a high rate and also place an administrative load (signaling overhead) on the wireless networks. High frequency of vertical handoff in urban areas can be reduced by considering individual users mobility pattern in making RAT-selection decisions.

Another aspect of geographical area heterogeneity is users' location which can be classified as indoor or outdoor. The location a user affects the quality of service received by the user, and the quality of reception also depends on whether the access point or base station of the wireless network is located indoor or outdoor. When comparing antennas located indoor or outdoor, indoor antennas usually have a shorter reception range but the outdoor antenna will generally allow much better signal reception. In [41], it has been shown that the throughputs obtained in LTE network for outdoor environments are more consistent than the throughputs obtained in indoor environments. Moreover, in the indoor environments, a lower average throughput is observed than in outdoor environment [41]. Different propagation models have been developed for indoor and outdoor environments, and effective use of appropriate model will ensure good quality of service.

Another aspect of geographical area heterogeneity is topography or terrain. The terrain over which a wireless network is deployed will impact the network due to its effects on signal propagation at a particular frequency. The terrain of a geographical area can be classified in different ways. For example, a terrain can be classified as flat, mountainous, water or foliage, based on natural environment. A terrain can also be classified as rural, sub-urban, or urban, based on manmade structures. Different propagation models have been developed for different terrains. Efficient use of appropriate signal propagation model in a given geographical area will ensure good quality of service and efficient utilizations of radio resources.

Availability of basic infrastructure needed to support wireless networks vary with different geographical areas. For example in some geographical areas, electricity infrastructure is readily available such that WLAN access points and cellular network base stations can easily be connected to electrical grid whereas in some geographical areas electricity infrastructure is nonexistent and therefore access points and base stations are primarily powered by batteries and diesel generators. Thus, in areas where electricity infrastructure is nonexistent, the cost or refueling and maintaining generators generally contributes to higher tariffs for network subscribers.

Legislation and spectrum availability are important factors that vary with geographical locations. Different countries of the world have different regulatory bodies that determine spectrum allocation policy. Legislation heterogeneity includes whether a particular frequency band is licensed or unlicensed, effective radiated power at any particular frequency [42], etc. In addition, wireless networks operating in licensed frequency bands are subject to regulatory control. A nation's regulatory body may decide not to auction some frequency bands that are required for some wireless networks in the country, and thereby hamper the quality and data rates of service deliver by network operators in the country. These regulation policies affect service pricing, quality of service provisioning, and competition among network operators.

Proneness to disaster and sabotage is another aspect of geographical area heterogeneity [43]. Certain regions of the world are more prone to disaster and sabotage than others. For example, in areas that are prone to natural disasters such as earthquake, hurricanes and tsunami, terrestrial networks deployed in such areas are easily affected by these events. Any of the events can cause destruction of network elements and disruption of network services. However, satellites access networks and high-altitude balloon networks are less susceptible to damage from natural disasters. Thus, in regions prone to natural disasters,

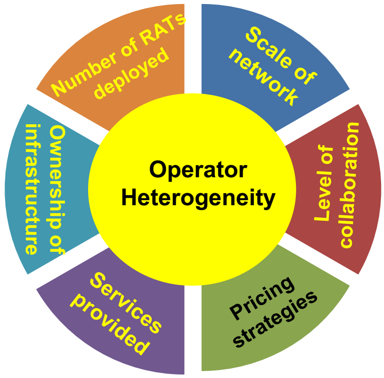


Fig. 6 Illustration of operators' heterogeneity

integration of terrestrial and satellite networks will ensure connectivity and some level of service continuity to multi-mode terminals that support these networks, in an event of natural disaster. Sabotage is another major problem in some geographical area where communication equipment are frequently vandalized or stolen, which often lead to network outages, and consequently poor quality of service and inefficient utilization of radio resources. Table 6 summarizes the different aspects of geographical area heterogeneity.

8 Comparisons of Some RAT-selection Algorithms with Respect to the Aspects of Wireless Network Heterogeneities Considered

Table 7 shows the comparison of some recent RAT-selection algorithms with respect to the six aspects of wireless network heterogeneities analyzed above. As shown in Table 7. RAT heterogeneity is the mostly considered aspect of wireless network heterogeneities while geographic area heterogeneity is the least considered aspect. In general, RAT, service, and users heterogeneities have received much attention in the development of radio resource management algorithms for wireless networks whereas terminal, operator, and geographical area heterogeneities have not been widely considered. Thus, researchers working of radio resource management for wireless networks need to give more attention to terminal, operator, and geographical area aspect of wireless network heterogeneities in order to have more holistic solutions to the problems of radio resource management in wireless networks.

Existing wireless networks are heterogeneous, and the different aspects of wireless network heterogeneities need to be taken into consideration in developing radio resource management algorithms. Clear understanding of wireless network heterogeneities will help researchers in developing more efficient radio resource management algorithms.

9 Proposed Network-Selection Algorithm

This paper proposes a network selection algorithm, which considers the six aspects of NWGN heterogeneities discussed above. Figure 8 illustrates the heterogeneous scenario considered in the proposed scheme. As shown in Fig. 8, two geographical areas, namely Area-P and Area-Q, are considered. Area-P has a moderate population density whereas Area-Q has a very high population density. Two network operators, namely Operator-A

Table 5 Operators/service provider heterogeneity

Heterogeneous features	Explanation	Classification	Effect on radio resource management and quality of service	Potential solution
Scale of network	The size of network own by a network operator	Operators can be classified as local, regional, national, or multi-national network operators	Scale of network affects service prices, and consequently service consumption	Economics of scale through collaboration among operators can reduce service prices
Number of RATs deployed	The number of different RATs deployed by an operator	Operators can be classified as single-RAT or multiple-RAT operators	A single RAT might not provide ubiquitous coverage and continuous high QoS levels, and cost effectiveness on services offered to users	Deployment of multiple RATs and joint management of radio resources will enhance quality of service and resource utilization
Ownership of network infrastructure	A licensed network operator owns the network equipment whereas a virtual network operator leases network equipment	Based on ownership of network infrastructure, operators can be classified as licensed network operator or virtual network operators	Virtual network operators promote competition among operators, which improves service consumption and radio resource utilization	Competition between licensed mobile network operator and mobile virtual network operator will reduce service price and enhance quality of service
Pricing strategies	Method of charging users for network services	Pricing strategy can be prepaid, postpaid, or hybrid. It can also be classified as fixed or dynamic pricing	It affects users' satisfaction and service consumption	Pricing can be used to incentivize users to consume more services. Pricing can also be used for congestion control
Services provided	Number or class of services provided by an operator	Operators can be grouped as single-service or multiple-service operators	The number of services provided by an operator affects users' service consumption and users' satisfaction	Different RATs are optimized to support different services. Joint management of radio resources can ensure that a service is delivered through the most suitable RAT for the service
Level of collaboration	Degree to which operators share network infrastructure and resources, which may include sites, towers, mast, cabinet, power, conditioning, access network, core network, and spectrum, among themselves	Level of operator collaboration among operators can be classified as no sharing' (no collaboration), passive infrastructure sharing, access network sharing, core network sharing, frequency spectrum sharing, and roaming-based sharing	Collaboration among operators reduces cost, extends coverage area, and enhances quality of service [39, 40]	Wireless networks' regulatory body of each nation can promote collaboration among operators by enacting appropriate rules and regulations

Fig. 7 Illustration of geographical areas' heterogeneity

and Operator-B, provide network services in the scenario. Operator-A is a national multi-RAT operator, which provides 2G and 3G co-located cellular networks in Area-P, and 2G, 3G, and LTE co-located cellular networks in Area-Q. Operator-B is a regional multi-RAT operator, which provides 2G and 3G co-located cellular networks in Area-Q. The 2G cellular network supports only voice service; the 3G network supports both voice and data services, and the LTE network supports data services. There are three types of mobile terminals used in the heterogeneous wireless network, namely MS-1, MS-2, and MS-3. MS-1 is a single-mode terminal that can connect to only 2G networks; MS-2 is a two-mode terminal that can connect to 2G and 3G networks; MS-3 terminals are three-mode terminals that can connect to 2G, 3G, and LTE networks. Operator-A has three groups of subscribers namely, U1, U2, and U3A. Group U1 are voice service subscribers who use terminal MS-1. Group U2 are voice and data services subscribers who use terminal MS-2, and Group U3A are voice and data subscribers who use terminal MS-3. Operator-B has only one group of subscriber called Group U3B. Group 3B subscribers are voice and data subscribers who use terminal MS-3.

In Fig. 8, the mobile terminal heterogeneities considered are terminal modality and services supported. The RAT heterogeneities considered is the service(s) supported in each RAT. The service heterogeneities considered are service class (voice and data), service type (new and handoff calls), and bandwidth requirements of each service class (bbu). The user heterogeneities considered are class of service demanded by users and user's device capability. The operators' heterogeneities considered are the scale of network and number of RATs deployed. The geographical area heterogeneity considered is population density, which impacts the number of available RATs.

Figure 9 is the flowchart of the proposed network selection algorithm for Operator A. As shown in Fig. 9, x and y are the amount of radio resources required for voice and data calls, respectively. R_n^v and R_h^v are the radio resources available for new voice calls and handoff voice calls, respectively, in the cell of a RAT, and R_n^d and R_h^d are the radio resources available for new data calls and handoff data calls, respectively, in the cell of a RAT. The flowchart for Operator B is much simpler because only one group of users (U3B) is involved.

Table 6 Geographical area heterogeneity

Heterogeneous features	Explanation	Classification	Effect on radio resource management	Potential solution
Population density	The number of people living per unit of an area	Based on population density, a geographical area can be classified as urban, sub-urban, or rural area	It determines the cell size of each base station, and the number of base station per unit area. It affects the frequency of vertical handoff, level of network congestion and quality of service	Small cell densification will reduce congestion in urban areas. Consideration of users' mobility pattern in making RAT-selection decisions will reduce the frequency of vertical handoffs
Geographic location	The location of a user within or outside a building	Geographic location can be classified as indoor or outdoor	It affects the signal reception and quality of service	Deployment of access points/base station in buildings, and the effective use of appropriate model will ensure good quality of service in different geographic locations
Topography	Topographical heterogeneity refers to the differences between two areas in terms of their physical characteristics	Topography can be classified as flat, mountainous, water or foliage, based on natural environment. It can also be classified as rural, sub-urban, or urban, based on manmade structures	It affects signal propagation and quality of service	Effective network planning and efficient use of appropriate signal propagation model in a given geographical area will ensure good quality of service and efficient utilizations of radio resources
Infrastructure availability	Availability of basic infrastructures needed for network deployment	Level of infrastructure available can be classified using linguistic terms such as poor, medium, or good	Level of existing infrastructure affects capital expenditure and operational expenditure on wireless networks, and consequently service price and consumption rates	Collaboration among operators will reduce capital and running costs on infrastructures, and consequently reduce service price
Legislation and spectrum availability	Regulation of the use of licensed frequency bands by individual nation's regulatory body	Spectrum regulation policies can be classified using linguistic terms such as poor, sufficient, good, or excellent	Availability of frequency spectrum determines level of services that can be provided and achievable data rate	Harmonization of frequency use across nations will ensure efficient use of spectrum, economy of scale based on mass market of communication equipment, and easy cross-border coordination between countries

Table 6 continued

Heterogeneous features	Explanation	Classification	Effect on radio resource management	Potential solution
Proneness to disaster and sabotage	Degree to which a particular region can be affected natural disasters or sabotage	Proneness to disaster and sabotage can be classified using linguistic terms such as very low, low, moderate, high, and very high	Natural disaster and sabotage can disrupt network services, affects quality of service, and radio resource utilization. Expansion of network coverage can be hampered by security concerns	Joint management of radio resources between terrestrial and satellite networks in regions prone to natural disasters can enhance quality of service and prevent total service disruption

Table 7 Comparison of RAT-selection algorithms considering six aspects of wireless network heterogeneities

S/N	RRM algorithm	Heterogeneity considered					
		Terminal	RAT	Service	User	Operator	Geographical area
1	Seo and Song [44]		√	√		√	
2	Falowo and Chan [2]		√	√	√		
3	Jocelyne et al. [36]			√	√	√	
4	Malanchini et al. [45]				√	√	√
5	Ramona et al. [1]		√	√	√		
6	Du et al. [46]		√	√			
7	Nguyen-Vuong et al. [3]		√	√	√		
8	Sgora et al. [4]		√	√	√		
9	Kosmidesa et al. [47]	√	√	√	√		
10	Chamodrakas et al. [5]		√	√	√		
11	Falowo et al. [48]	√	√	√			
12	Lopez-Benìtez et al. [49]		√	√			
13	Gozalvez et al. [6]		√	√	√		
14	Choque et al. [50]		√			√	
15	Suleiman et al. [51]		√		√		
16	Omhenia et al. [52]		√	√	√		
17	Gelabert, et al. [53]	√	√	√	√		
18	Vucevic et al. [54]		√		√		√
19	Preethi et al. [55]		√		√		
20	Xie et al. [56]		√		√		
21	Sibanda et al. [57]		√	√			
22	Konka et al. [58]		√		√	√	
23	Lee et al. [59]		√	√	√		
24	Falowo et al. [60]		√	√			
25	Zhu et al. [61]		√		√		

9.1 Performance Evaluation

In this section, the performance of the proposed scheme is evaluated in terms of the connection-level quality of service, call blocking/dropping probability. For simplicity, in both Area A and Area B, a group of overlapping (co-located) cells is considered in the HWN of each network operator. The correlation between the groups of co-located cells results from handoff connections between the cells of corresponding groups. For each operator, the state space of a group of collocated cells in the HWN in a particular area can be represented by a (2 * J * K)-dimensional vector given as:

$$\Omega = \left(m_{i,j}, n_{i,j} : i = 1, \ \ldots, K, \quad j = 1, \ldots, J\right) \tag{1}$$

For each operator, the non-negative integer $m_{i,j}$ denotes the number of ongoing new class-i calls in RAT j, and the non-negative integer $n_{i,j}$ denotes the number of ongoing

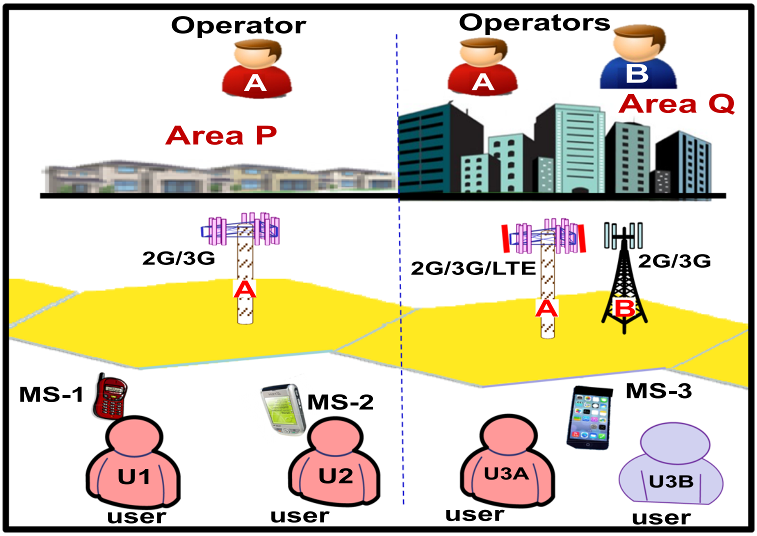


Fig. 8 Heterogeneous scenario considers in the proposed network selection algorithm

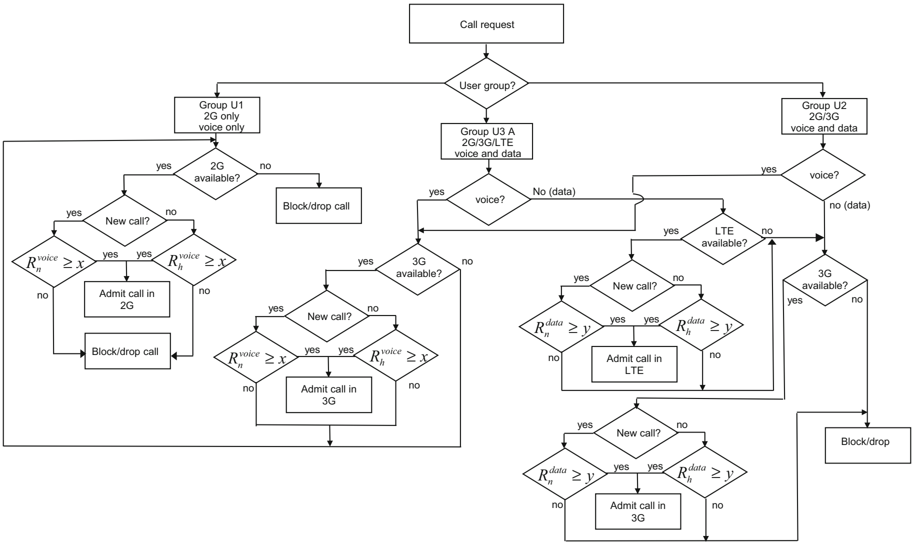


Fig. 9 Flowchart of the proposed network selection algorithm for Operator A

handoff class-i calls in RAT j in the group of collocated cells, where J is the number of RATs available in that particular area, and K is the number of services supported.

Let S denote the state space of all admissible states of the group of collocated cells as it evolves over time. An admissible state $\boldsymbol{s}$ is a combination of the numbers of users in each class that can be supported simultaneously in the group of co-located cells while maintaining adequate QoS and meeting resource constraints. In each operator's network, let T_j be threshold for rejecting new calls in RAT j and let b_i be the number of basic bandwidth unit (bbu) allocated to class-i service (call).

For each operator's network, the state S of all admissible states in the HWN is given as:

$$S = \left\{ \Omega = (m_{i,j},\ n_{i,j} : i = 1,\ \ldots, K,\quad j = 1, \ldots, J) : . \right.$$
$$\left. \sum_{i=1}^{K} m_{i,j}\ .\ b_i \le T_j\ \ \forall j \quad \wedge \sum_{i=1}^{K} (m_{i,j} + n_{i,j})\ .\ b_i\ \le C_j\ \ \forall j \right\} \tag{2}$$

RAT selection decisions are made in the arrival epoch. Every time a new call or a set of handoff calls arrives in the group of co-located cells in a particular location, the RAT-selection algorithm decides whether it can accept the call and in which RAT to admit the call. If a call cannot be admitted into the HWN because there is not enough bbu, it is blocked/dropped.

Following the general assumption in wireless networks, new and handoff class-i calls arrive in each cell in Area z (z ∈ {P, Q}) in the HWN according to Poisson process with rate ${}^{z}\lambda_i^n$ and ${}^{z}\lambda_i^h$ respectively. Let ${}^{z}\rho_{new_{i,j}}$ and ${}^{z}\rho_{han_{i,j}}$ denote the load generated by new class-*i* calls and handoff class-*i* calls, respectively, in RAT-*j* in Area z. Let $1/{}^{z}\mu_i^n$ and $1/{}^{z}\mu_i^h$ denote the channel holding time of new class-i call and handoff class-i call respectively, in Area z and let ${}^{z}\lambda_{i,j}^n$ and ${}^{z}\lambda_{i,j}^h$ denote the arrival rates of new class-i call and handoff class-i call in RAT j, respectively in Area z, then,

$${}^{z}\rho_{new_{i,j}} = \frac{{}^{z}\lambda_{i,j}^n}{{}^{z}\mu_i^n} \quad \forall\ i,j, \tag{3}$$

$${}^{z}\rho_{han_{i,j}} = \frac{{}^{z}\lambda_{i,j}^h}{{}^{z}\mu_i^h} \quad \forall\ i,j \tag{4}$$

From the steady state solution of the Markov model, performance measures of interest can be determined by summing up appropriate state probabilities. Let $P^z(s)$ denotes the steady state probability that system is in state ***s*** (***s*** ∈ ***S***) in Area z. From the detailed balance equation, $P^z(s)$ is obtained as:

$$P^z(s) = \frac{1}{G} \prod_{i=1}^{K} \prod_{j=1}^{J} \frac{\left({}^{z}\rho_{new_{i,j}}\right)^{m_{i,j}}}{m_{i,j}!} \frac{\left({}^{z}\rho_{han_{i,j}}\right)^{n_{i,j}}}{n_{i,j}!} \quad \forall\ s \in S \tag{5}$$

where G is a normalization constant in Area z is given by:

$$G^z = \sum_{s \in S} \prod_{i=1}^{K} \prod_{j=1}^{J} \frac{\left({}^{z}\rho_{new_{i,j}}\right)^{m_{i,j}}}{m_{i,j}!} \frac{\left({}^{z}\rho_{han_{i,j}}\right)^{n_{i,j}}}{n_{i,j}!} \tag{6}$$

9.2 New Call Blocking Probability

In Area z, a new class-i call is blocked in the group of co-located cells if none of the available RATs that support the new class-i call has enough bbu to accommodate the new call with the bandwidth requirements. Let ${}^{w}S_{bi}^{z} \subset S$ denote the set of states in which a new class-i call from user w (w ∈ {U1, U2, U3A} for Operator A and (w ∈ {U3B} for Operator B) is blocked in the group of co-located cells in area z (z ∈ {p, q}. It follows that

$$
{}^{w}S_{bi}^{z} = \left\{ s \in \ \mathrm{S} \ : \ \left(b_i + \sum_{i=1}^{K} (m_{i,j} \ + n_{i,j}).\, b_i \ > T_i \ \vee b_i + \sum_{i=1}^{K} (m_{i,j} \ + n_{i,j}).\, b_i \ > C_i \right) \right.
$$
$$
\left. \forall\, j \in h_{w,z} \right\}. \tag{7}
$$

where $h_{w,z}$ is the set of indices of RATs of an operator's network that supports class-i calls from user w in area z. Thus the blocking probability, ${}^{w}P_{bi}^{z}$, for new class-i call from user w in the group of co-located cell in Area z is given as:

$$
{}^{w}P_{bi}^{z} \ = \sum_{s \in {}^{w}S_{bi}^{z}} P^{z}(s) \tag{8}
$$

9.3 Handoff Call Dropping Probability

In Area z, a handoff class-i call is dropped in the group of co-located cells in if none of the available RATs that support the handoff class-i call has enough bbu to accommodate the handoff call with the bandwidth requirements. Let ${}^{w}S_{di}^{z} \subset S$ denote the set of states in which a handoff class-i call from user w (w ∊ {U1, U2, U3A} for Operator A and (w ∊ {U3B} for Operator B) is dropped in the group of co-located cells in area z (z ∊ {p, q}. It follows that

$$
{}^{w}S_{di}^{z} = \left\{ s \in \ \mathrm{S} \ : \ \left(b_i + \sum_{i=1}^{K} (m_{i,j} \ + n_{i,j}).\, b_i \ > C_i \right) \ \forall\, j \in h_{w,z} \right\}. \tag{9}
$$

Thus the dropping probability, ${}^{w}P_{di}^{z}$, for handoff class-i call from user w in the group of co-located cell in Area z is given as:

$$
{}^{w}P_{di}^{z} \ = \sum_{s \in \ {}^{w}S_{di}^{z}} P^{z}(s) \tag{10}
$$

9.4 Simulation Results

The performance of the proposed scheme is evaluated through simulation in this subsection. The simulation parameters used are shown in Table 8. Other parameters used are: ${}^{Q}\lambda_1{}^{n} = [1,\ 10\,]$, ${}^{P}\lambda_1^{n} = {}^{Q}\lambda_1^{n}$, ${}^{P}\lambda_1{}^{h} = 0.5\,{}^{P}\lambda_1^{h}$, ${}^{Q}\lambda_2^{n} = [1,\ 10\,]$, ${}^{P}\lambda_2^{n} = {}^{Q}\lambda_2^{n}$, ${}^{P}\lambda_2^{h} = 0.5\,{}^{P}\lambda_2^{h}$, ${}^{Q}\mu_2^{n} = {}^{Q}\mu_2^{h} = 0.5$, ${}^{P}\mu_2^{n} = {}^{P}\mu_2^{h} = 0.5$, ${}^{Q}\mu_1^{n} = {}^{Q}\mu_1^{h} = 0.5$, ${}^{Q}\mu_1^{n} = {}^{Q}\mu_2^{n} = 0.5$. For simplicity, RAT-1 has the same value for Operator A and Operator B. Similarly RAT-2 has the same value for the two operators, while RAT-3 is unique to Operator-A.

Figure 10 shows the effect of mobile terminal heterogeneity on call blocking/dropping probabilities. As shown in Fig. 10, U1 and U2 both subscribe to voice service in Operator-A's network, and are in Area P. However, a subscriber in U1 having a new voice call on a single-mode terminal (voice_new_U1) experiences a higher voice call blocking probability than a subscriber in U2 having a new voice call on a dual-mode terminal (voice_new_U2). Similarly, a subscriber in U1 having a handoff voice call on a single-mode terminal (voice_hand_U1) experiences a higher voice call blocking probability than a subscriber in

Table 8 Simulation parameters

RATs	RAT capacity (bbu)	RAT threshold (bbu)	RAT's service class	Bandwidth required for service class (bbu)
RAT 1 (2G)	$C_1 = 8$	$T_1 = 4$	Voice (class 1)	$b_1 = 1$
RAT 2 (3G)	$C_2 = 12$	$T_2 = 5$	Voice (class 1) and data (class 2)	$b_1 = 1$, $b_2 = 4$
RAT 3 (LTE)	$C_3 = 16$	$T_3 = 8$	Data (class 2)	$b_2 = 4$

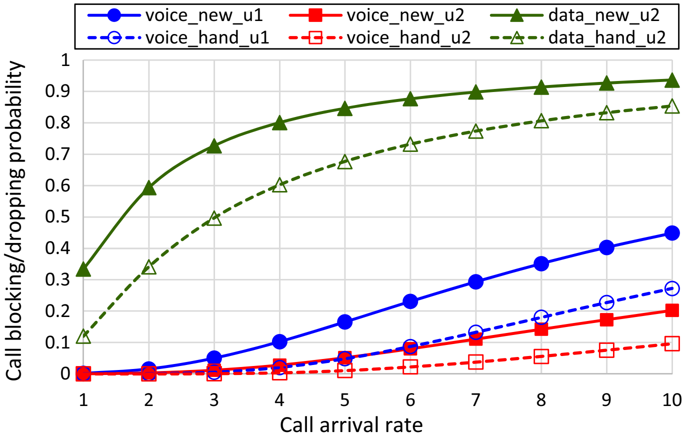


Fig. 10 Effect of mobile terminal, RAT, and user heterogeneities on call blocking/dropping probability

U2 having a handoff voice call on a dual-mode terminal (voice_hand_U2). Thus terminal heterogeneity affects connection-level QoS.

Figure 10 also shows the effect of RAT heterogeneity because RAT 1 supports only voice whereas RAT 2 supports both voice and data calls. Thus, a data call from a subscriber in U2 cannot be accepted in RAT 1 (blocked) whereas it can be accepted into RAT 2. Moreover, Fig. 10 shows the effect of user heterogeneity in the sense that subscribers in U1 are single-service (voice only) users whereas subscribers in U2 and dual-service (voice and data) users. If all the users are single service (voice) users, the overall call blocking/dropping probability will be less because a data call requires more bbu than a voice call.

Figures 11 and 12 show the effect of operators' heterogeneity on call blocking/dropping probability. As shown in Fig. 11, subscribers in U3A and subscribers in U3B all use three-mode terminals, and are in the same geographical location (Area-Q) but belong to different operators. As shown in Fig. 11, U3A subscribers experience lower new voice call blocking probability (voice_new_U3A) than new voice call blocking probability (voice_new_U3B) experienced by U3B subscribers. Moreover, U3A subscribers experience lower handoff voice call dropping probability (voice_hand_U3A) than handoff voice call dropping probability (voice_drop_U3B) experienced by U3B subscribers. The reason for this is simply that Operator-A has deployed the LTE network in Area-Q, which carries much of the data traffic from U3A, and thereby free resources in the 3G network for voice calls whereas Operator-B has not deployed LTE, therefore all the data traffic are carried through

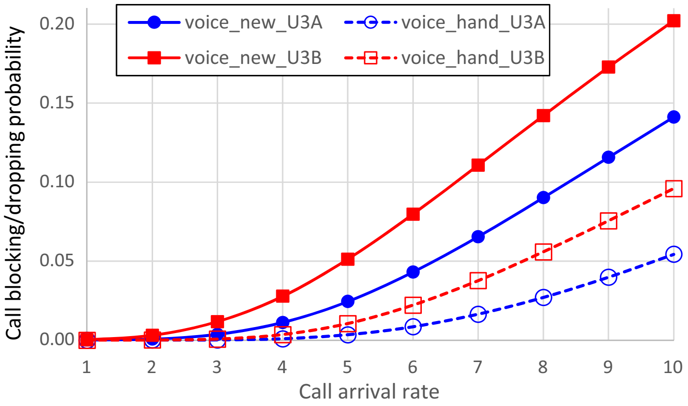


Fig. 11 Effect of operator heterogeneity on voice call blocking/dropping probability

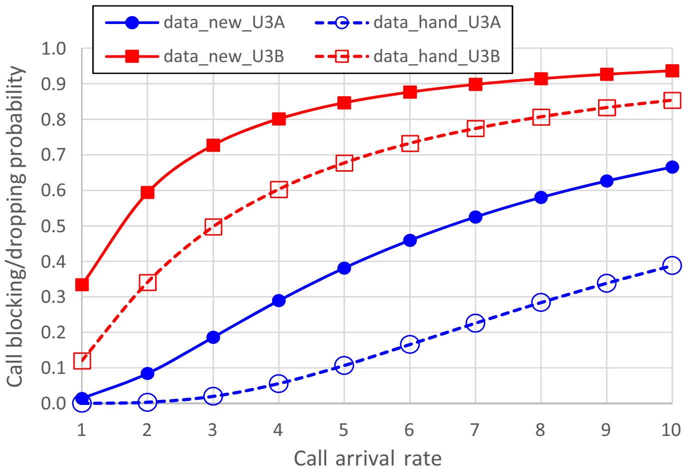


Fig. 12 Effect of operator heterogeneity on data call blocking/dropping probability

3G network. Thus, operators' heterogeneities impact the quality of service experience by their respective subscribers.

Figure 12 shows that the new data call blocking probability (data_new_U3A) from U3A subscribers is less than the corresponding new data call blocking probability (data_new_U3B) from U3B subscribers. Moreover, it shows that the handoff data call dropping probability (data_hand_U3A) from U3A subscribers is less than the corresponding handoff data call dropping probability (data_hand_U3B) from U3B subscribers. Thus, operators' heterogeneities impact the quality of service experience by their respective subscribers.

Figures 13 and 14 show the effect of service heterogeneity on call blocking/dropping probabilities, considering subscribers in group U3A. As shown in Fig. 13, the blocking probability for new data calls (data_new_AP) is higher than the corresponding blocking probability for new voice calls (voice_new_AP) in Area-P because of service heterogeneity (i.e. the data calls require more bbu than the voice calls). Similarly, the blocking probability for new data calls (data_new_AQ) is higher than the corresponding blocking

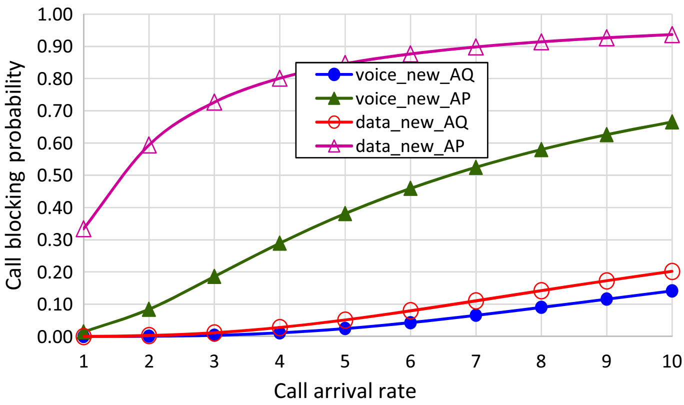


Fig. 13 Effect of service and geographical area heterogeneities on new call blocking probability

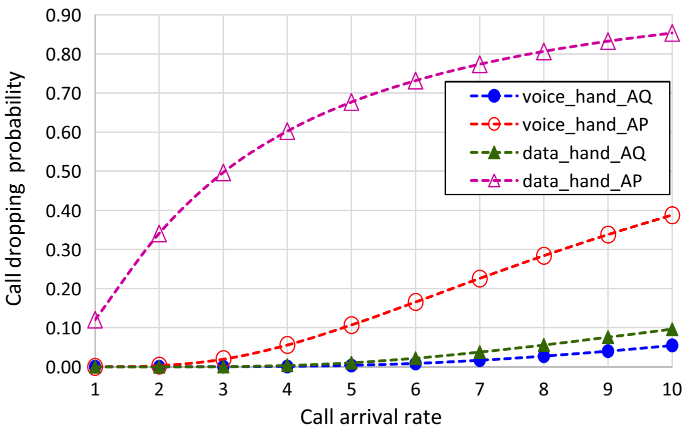


Fig. 14 Effect of service and geographical area heterogeneities on handoff call dropping probability

probability for new voice calls (voice_new_AQ) in Area-Q because of service heterogeneity. Figure 14 shows that the dropping probability for handoff data calls (data_-hand_AP) is higher than the corresponding dropping probability for handoff voice calls (voice_
hand_AP) in Area-P. Similarly, the dropping probability for handoff data calls (data_ hand_AQ) is higher than the corresponding dropping probability for handoff voice calls (voice_hand_AQ) in Area-Q because of service heterogeneity.

Figures 13 and 14 also show the effect of geographical area heterogeneity on call blocking/dropping probabilities, considering subscribers in group U3A. When a subscriber in U3A moves from Area-Q to Area-P, he will experience different degrees of connection-level quality of service because of geographical area heterogeneity. In Fig. 13, for a subscriber in UA3, the blocking probability of a new voice call in Area P (voice_new_AP) is higher than the corresponding blocking probability for a new voice call in Area-Q (voice_new_AQ). The same trend is observed for a new data call in Area P and Area-Q. Moreover, In Fig. 14, the dropping probability for a handoff voice call in Area P (voice_hand_AP) is higher than the corresponding dropping probability for handoff voice call in Area-Q (voice_hand_AQ). The same is observed for handoff data calls in Area-P and Area-Q. The reason is that in Area-Q, a U3A subscriber can access three available RATs deployed by Operator-A, whereas in Area-P, the subscriber can access only two available RATs deployed by Operator A. Thus, geographical area heterogeneity affects connection-level QoS in wireless network of the same operator.

10 Conclusion

This paper has examined wireless network heterogeneities from six different perspectives namely mobile terminals, radio access technologies (RATs), network services, users, network operators, and network geographical areas. The paper then analyzed the different aspects of wireless network heterogeneities and compared existing network-selection schemes proposed for radio resource management based of the six aspects of the wireless network heterogeneities. Comparative analysis of the different network-selection algorithm shows that whereas RAT, services, and users heterogeneities have received much attention in the literature, terminal, operator, and geographical area heterogeneities have not been widely considered. Thus, more attention should be given to terminal, operator, and geographical area aspects of wireless network heterogeneities. Comprehensive knowledge of the different aspects of wireless network heterogeneities, as well as their challenges on efficient radio resource management and quality of service provisioning in wireless networks will help researchers in developing more efficient radio resource management algorithms. An illustrative algorithm that considers the different aspects of network heterogeneity has been evaluated, and simulation results are given to highlight the effects of network heterogeneity on connection-level quality of service provisioning in heterogeneous wireless networks.

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Olabisi E. Falowo received his Ph.D. in Electrical Engineering at the University of Cape Town in 2008. He is currently an Associate Professor in the same department. He has published over 50 technical papers in peer-reviewed conference proceedings and journals including Elsevier Computer Communications, Elsevier Computer Networks, EURASIP Journal on Wireless Communications and Networking, and Wiley Wireless Communications and Mobile Computing, and Telecommunication Systems. His primary research interest is in radio resource management in heterogeneous wireless networks. Olabisi Falowo is a senior member of the IEEE.