MOBILE CONVERGED NETWORKS: FRAMEWORK, OPTIMIZATION, AND CHALLENGES

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ABSTRACT

In this article, a new framework of mobile converged networks is proposed for flexible resource optimization over multi-tier wireless heterogeneous networks. Design principles and advantages of this new framework of mobile converged networks are discussed. Moreover, mobile converged network models based on interference coordination and energy efficiency are presented, and the corresponding optimization algorithms are developed. Furthermore, future challenges of mobile converged networks are identified to promote the study in modeling and performance analysis of mobile converged networks.

INTRODUCTION

Currently, wireless communication networks are widely deployed in every scenario of human society, which includes short-distance transmission (e.g., Bluetooth communications in wireless mice), long -distance transmission (e.g., space transmission between the Earth and Mars), and so on. Although the above networks and application scenarios are quite different, multi-mode communications have adopted more and more communication standards and technologies into a common user terminal. For instance, a smart mobile phone usually supports a cellular network, a wireless local area network (WLAN), Bluetooth and near field communication, and so on. Based on multi-mode communications, different types of wireless heterogeneous networks can be converged into a uniform mobile network (i.e., the mobile converged network) [1, 2]. A typical mobile converged network is illustrated by Fig. 1, in which the cellular network, WLAN, and wireless sensor network (WSN) are converged.

Studying mobile converged networks has attracted much attention in recent years, especially the topic of converged mobile cellular networks and WSNs. Han proposed an authentication and key agreement protocol that efficiently reduces the overall computational and communication costs in the next generation converged network [3]. A system architecture and application requirement for converged mobile cellular networks and WSNs was introduced, and then the joint optimization of converged networks for machine-to-machine communications was discussed in [4]. An energy-efficient data collection scheme in a converged WSN and mobile cellular network was proposed for improving energy efficiency [5]. A quality of service (QoS)-guaranteed resource scheduling algorithm and a railway resource grab mechanism in a high-speed environment was presented to ensure QoS for users and timely transmission of railway signals in mobile converged networks [6]. Bae proposed a new concept of converged service based on digital multimedia broadcast and wireless networks [7]. After considering the network operation cost, the performance trade-off between the network QoS and the network operation cost for intersystem soft handover in the converged digital video broadcasting for handhelds and a Universal Mobile Telecommunications System network was modeled using a stochastic tree [8]. A framework combining clouds and distributed mobile networks was presented [9], of which mobile converged networks can take advantage. An efficient network selection mechanism was presented to guarantee that mobile users select the most appropriate wireless network to connect from heterogeneous wireless networks using the theory of games [10].

In all the aforementioned mobile converged network studies, modeling and performance analysis for detail scenarios were discussed, and most mobile converged networks consisted of two types of wireless networks. However, there is not a general framework of mobile converged networks that covers multi-tier wireless heterogeneous networks. Motivated by the above gaps, we propose a new framework of mobile converged networks that not only covers the main characteristics of mobile converged networks but also includes different types of wireless heterogeneous networks.

The remainder of this article is outlined as follows. A new framework of mobile converged networks is proposed to support multi-tier heterogeneous networks. Moreover, two algorithms are developed to improve the performance of mobile converged networks. Based on the presented results, future challenges for mobile converged networks are given, followed by conclusions drawn in the last section.

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A Framework of Mobile Converged Networks

To converge different types of wireless communication technologies into a mobile network, two problems have to be solved. First, a converged scheme should be presented by investigating the characteristics of different types of wireless communication technologies to avoid potential technology conflicts. Second, the performance evaluation of mobile converged networks is another issue that involves the selection of evaluation subjects, evaluation approaches, validation of evaluations, the analysis of evaluation data, and so on.

Based on the aggregation of each tier model of a heterogeneous network, the mobile converged network framework can be directly built by defining the multi-association node relationship in multi-tier heterogeneous networks. However, it is difficult to analyze and optimize the resource schedule of mobile converged networks when many variables are involved in the aggregation of each tier model of heterogeneous networks. Moreover, it becomes impossible to optimize the resource schedule in mobile converged networks when the calculation complexity obviously increases with increased network sizes. Therefore, it is a critical problem to build a new framework for mobile converged networks with limited complexity and enough flexibility for future wireless heterogeneous networks.

In order to reduce the number of variable types in converged heterogeneous networks, variable mapping is considered as an important approach to build a framework of mobile converged networks. For example, transmitters in different tiers of wireless heterogeneous networks usually have different transmission power. To evaluate the impact of transmission power from different tier wireless heterogeneous networks on the mobile converged networks, locations of transmitters can be scaled into a framework of a mobile converged network by accounting for path loss effect over wireless channels. In the new framework of mobile converged networks, the transmission power from difference tiers of wireless heterogeneous networks is normalized, and locations of transmitters are scaled to ensure that the signal-to-interference-plus-noise ratio (SINR) at receivers in a mobile converged network are equivalent to the SINR at receivers in multi-tier wireless heterogeneous networks. As a consequence, a new framework of mobile converged networks can be presented by variable mapping in wireless heterogeneous networks. Moreover, based on the allocation, the interaction of different tiers of wireless heterogeneous networks is classified as the non-conflict and conflict domains in the framework of mobile converged networks for optimizing the resource schedule. A conflict domain includes multi-tier heterogeneous networks with interference between each other, and a non-conflict domain includes multi-tier heterogeneous networks without interference between each other.

The network topology of wireless heterogeneous networks is affected by wireless access methods, infrastructures, mobility, and relay of user terminals. Therefore, all the above factors should be included in the new framework of mobile converged networks by mapping a uniform network topology. Based on the random network topology mapping approach, a uniform network topology of a mobile converged network is illustrated in Fig. 2. First, even for nodes that have multi-mode capability, different links of a multi-mode node are mapped into virtual multi-tier wireless heterogeneous networks as multiple links which are separated into multiple mapped single-mode nodes with different transmission locations. Then, using virtual infinite-bandwidth inter-node links to connect them, these single-mode nodes at virtual multi-tier wireless heterogeneous networks are mapped as a functional single node into a uniform network topology of a mobile converged network.

In the uniform network topology of a mobile converged network, all infrastructure stations and user terminals are normalized as mobile converged network nodes, and all wireless links of wireless heterogeneous networks are normalized as mobile converged network links. Therefore, the uniform network topology of mobile converged networks is formulated as (Φ^C, L^C), where Φ^C is the node set of mobile converged networks and L^C is the link set of mobile converged networks. Compared to aggregated multi-tier wireless heterogeneous networks, the

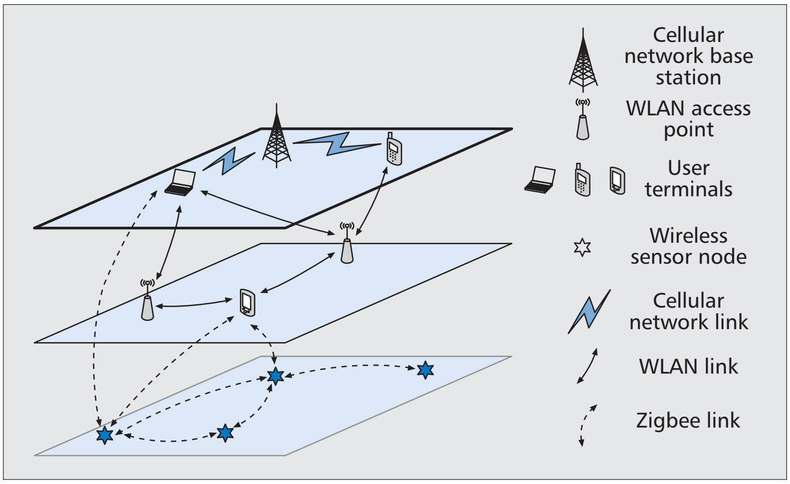

Figure 1. A typical mobile converged network.

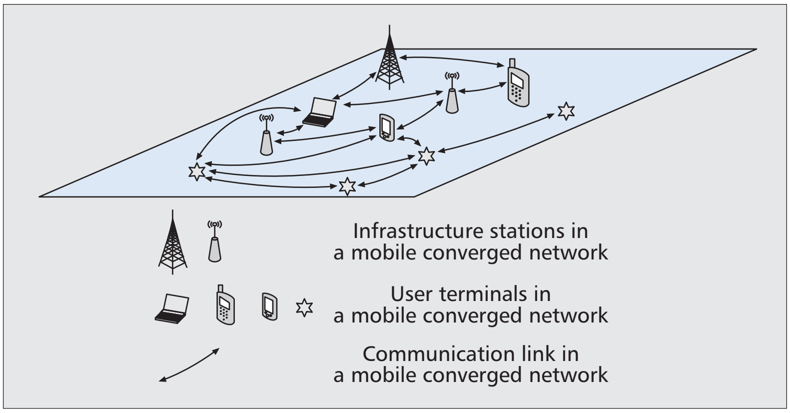

Figure 2. A random network topology of a mobile converged network.

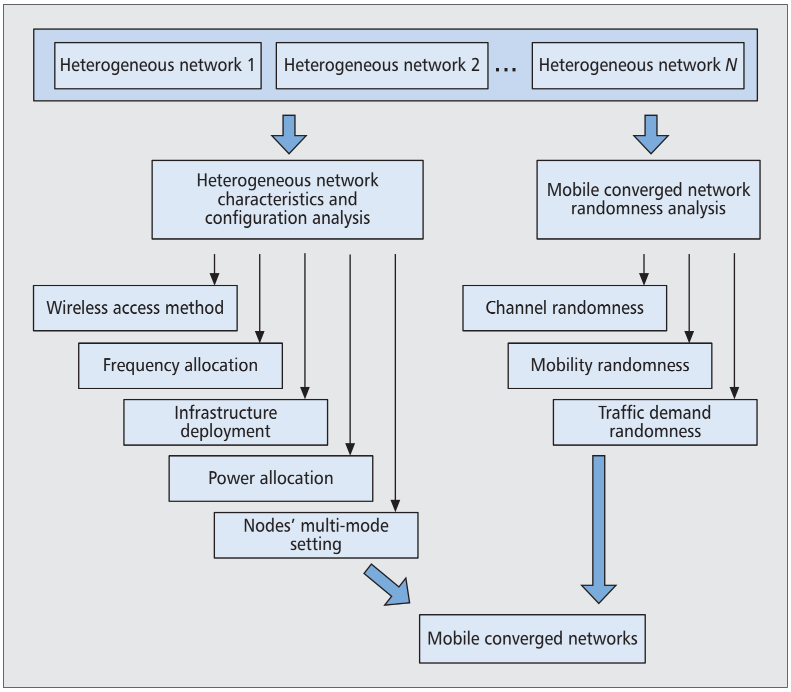

Figure 3. The new framework for mobile converged networks.

performance analysis of mobile converged networks is simplified by a uniform network topology.

For example, considering the downlinks in K-tier heterogeneous cellular networks, the base stations (BSs) in tier k have transmit power P_k and the distribution of BSs follows a point process [11] Φ_k^{BS}. Without loss of generality, a mobile station (MS) MS_y is assumed to be located at the origin coordinate $\mathbb{O}$, the signal power $P_{\mathrm{BS}_x \mathrm{MS}_y}$ received by the MS MS_y from a BS BS_x located at x is

$$P_{\mathrm{BS}_x \mathrm{MS}_y} = P_k \|x - \mathbb{O}\|^{-\alpha} = 1 \cdot \left(P_k^{-(1/\alpha)} \|x - \mathbb{O}\|\right)^{-\alpha} = 1 \cdot \|P_k^{-(1/\alpha)} \cdot x - \mathbb{O}\|^{-\alpha} \quad (1)$$

where 1 is the normalized transmission power, α is the path loss factor from BS_x to MS_y at origin $\mathbb{O}$, and $\|\cdot\|$ is the distance operator.

Equation 1 means that the signal power received by MS_y at the origin is exactly equal to the signal power transmitted from a virtual BS with transmit power 1 and located at $P_k^{-(1/\alpha)} \cdot x$, where $P_k^{-(1/\alpha)}$ is the scaling law used for the distance from origin $\mathbb{O}$ to BS_x. Centered with origin $\mathbb{O}$, which we call the transmission power normalized center, the point process Φ_k^{BS} can be scaled to the point process $\Phi_k^{\mathrm{BS}\prime} = P_k^{-(1/\alpha)} \cdot \Phi_k^{\mathrm{BS}}$, in which the virtual BSs with transmission power 1 transmit the same signal power (or interference power) to the origin MS as the original BSs in Φ_k^{BS} do. We scale the point processes in all tiers to normalize the transmit power to 1, and then combine them into a point process $\Phi^C = \cup_{k=1}^{K} P_k^{-(1/\alpha)} \cdot \Phi_k^{\mathrm{BS}}$, while keeping the link set L^C the same as the network links before scaling. In the end, the uniform network topology of mobile converged networks is given.

However, there are still many issues in building the new framework for mobile converged networks. Two main issues are summarized as follows:

- The uniform description issue of different wireless access methods. It is well known that the wireless access method has great impact on wireless link management, interference coordination, transmission rate, spectrum efficiency, and energy efficiency in wireless networks. It is difficult to analyze the impact of different wireless access methods on the performance of mobile converged networks by one parameter.
- The location issue of the transmission power normalized center. In the view of statistics, the transmission power normalized center of mobile converged networks can be located at an arbitrary point without any impact of signal/interference analysis on the mobile converged network. However, different locations of the transmission power normalized center will affect the random network topology and network router models. Consequently, location optimization of the transmission power normalized center is another key issue in the framework of mobile converged networks.

Motivated by the above gaps, we propose a new framework of mobile converged networks to cover multi-tier wireless heterogeneous networks in Fig. 3. The new framework for mobile converged networks is divided into two parts: one part of the framework is the characteristics and configurations of wireless heterogeneous networks, including wireless access methods, frequency allocation, infrastructure deployment, power allocation, and configuration of multimode nodes; the other part of the framework is about the randomness of wireless heterogeneous networks, including wireless channel randomness, mobility randomness, and traffic demand randomness.

Modeling of Mobile Converged Networks Based on Interference Coordination

Interference coordination is always an important challenge for wireless communication systems. It is well known that interference coordination is related to the capacity, transmission rate, spectrum efficiency, and energy efficiency in wireless networks. Based on the proposed framework for mobile converged networks, we explore building a mobile converged network model accounting for co-channel interference among multi-tier wireless heterogeneous networks.

Based on the proposed framework for mobile converged networks, multi-tier wireless heterogeneous networks are mapped into a mobile converged network with a uniform network topology. However, the uniform network topology is just based on links in wireless heterogeneous networks. The links affected by co-channel interference of mobile converged networks are not mapped into the uniform network topology. For the mobile converged network model based on interference coordination, node links of mobile converged networks are adjusted by relationships between interfering transmitters and receivers. Furthermore, the coordinate locations of the transmitters in mobile converged networks are scaled by considering the transmission power of interfering transmitters and distances between the interfering transmitters and receivers. The random topology of mobile converged networks based on interference coordination is illustrated in Fig. 4, where solid lines denote desired signal links and dashed lines denote interference links.

Considering interference coordination, a uniform network topology with desired signal links and interference links is derived for mobile converged networks. Furthermore, cross-tier routing algorithms can be developed by utilizing the relay capability of multi-mode nodes to minimize co-channel interference in mobile converged networks. The main idea of cross-tier routing algorithms is to maximize distances between interfering transmitters and receivers. To satisfy this requirement, data traffic is relayed by multi-mode nodes with different frequency bands in a mobile converged network. In this case, the co-channel interference could be minimized with guaranteed throughput. Therefore, the joint optimization solution involves the frequency, spatial, and temporal dimensionalities of mobile converged networks. However, the mobile converged network model based on interference coordination is an open question considering the challenges listed below.

Time-variant wireless channels. Time-variant wireless channels affect the capacity and bit error rate of wireless links, and even interrupt wireless links in mobile converged networks. In this case, the topology of the networks is affected by time-variant wireless channels. Accordingly, the interference model should support the dynamic network topology affected by time-variant wireless channels.

Spatial randomness of interfering transmitters. In mobile converged networks, the associating relationship among multi-mode nodes is flexible for minimizing co-channel interference. However, it is a complex problem to build the interference conflicting model when the network topology is changed by relationships between multi-mode nodes and user terminals.

Mobility randomness of user terminals. In mobile converged networks, user terminal locations are usually assumed to follow a random process. Moreover, the mobility model of user terminals also follows another random process. However, it is very difficult to model the mobility of user terminals because the mobility model and the location model follow different random processes.

Based on the mobile converged network model with interference coordination, the interference minimizing algorithm of mobile converged networks is presented in Algorithm 1.

In the conventional SINR scheme of mobile converged networks, user terminals are associated with infrastructure stations based on the maximal SINR value received at the user terminal. In this case, every user terminal just associates with an infrastructure station based on its own SINR performance without considering interference at other user terminals. As a consequence, one user terminal may obtain the most optimal performance, but the average interference of mobile converged networks is obviously increased. Contrary to the conventional SINR scheme, Algorithm 1 tries to decrease the average interference at user terminals to improve the total performance of mobile converged networks. In every loop of interference optimization, the cross-tier route for transmission detours to the tier in which the least interference is generated and the most interference tolerance remains. Based on Algorithm 1, simulation results of the interference minimizing and conventional SINR schemes are compared in Fig. 5. In the simulations of Fig. 5, a three-tier wireless heterogeneous network is configured with corresponding infrastructure station density denoted by 1:0.1:0.01, and the intensity of user terminals is also normalized by these densities of tiers. User terminals are governed by a Poisson point process with intensity λ and their mobility subject to a Gaussian-Markov mobility model [12], and every user terminal can access one tier of wireless heterogeneous networks based on different association schemes. From the curves in Fig. 5, the normalized average interference of mobile converged networks with the interference minimizing scheme is less than the normalized average interference with the conventional SINR scheme under different path loss factors. Figure 5 illustrates that the normalized average interference increases with increasing normalized intensity of user terminals, because the shorter distance of user terminals is conducive to higher interference.

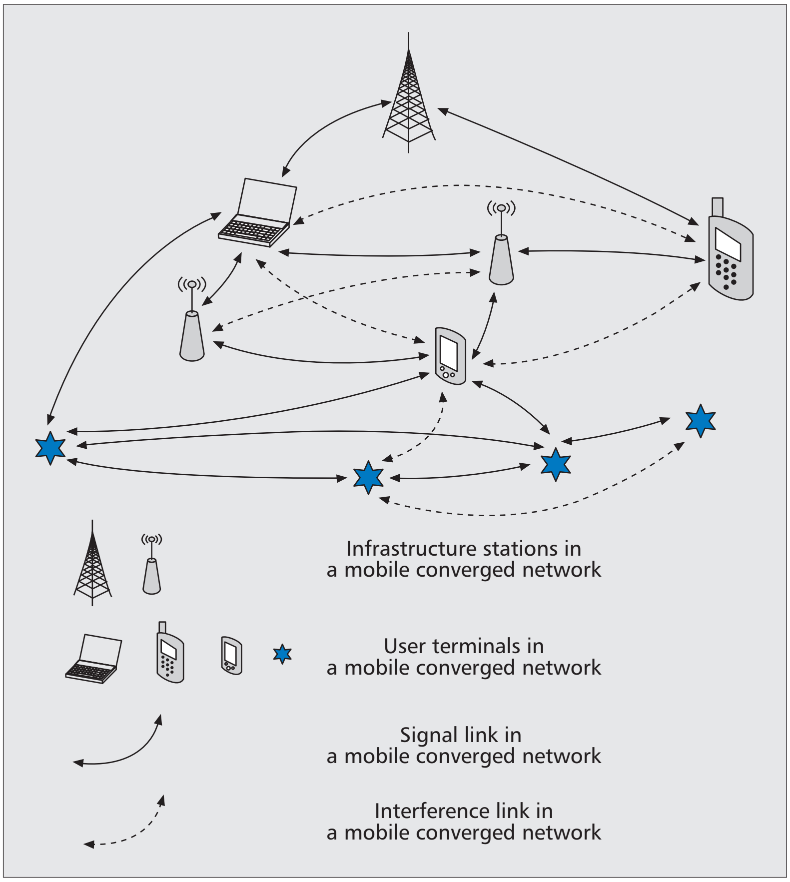

Figure 4. Network topology of mobile converged networks based on interference coordination.

Modeling of Mobile Converged Networks Based on Energy Efficiency

The energy efficiency of wireless networks is defined as how many bits can be transmitted by consuming 1 J energy in wireless networks. Because mobile converged networks have characteristics of multi-network spatial overlay and multi-mode configuration in transmitters, they are recommended as one potential solution to improve energy efficiency in future wireless networks. The heterogeneous characteristics of mobile converged networks provide many degrees of freedom to optimize the energy efficiency of data transmission [13].

When multi-tier wireless heterogeneous networks are mapped into a uniform network topology, weighting vectors are added into links of the uniform network topology to build a directed graph. On the other hand, we can also configure the maximal power consumption threshold in specified nodes of mobile converged networks. It is necessary to build the maximal network flow model considering multi-dimensionality randomness. Furthermore, the energy efficiency optimization solution is based on the trade-off of the energy consumption and network flow in the frequency, spatial, and temporal dimensions [14]. Algorithm 2 is the energy efficiency optimization algorithm of mobile converged networks, in which energy consumption of every possible cross-tier link is evaluated to maximize the energy efficiency of mobile converged networks.

To evaluate the performance of the proposed energy efficiency optimization algorithm, simulation results are compared between the conventional SINR scheme and the energy efficiency optimization scheme in Fig. 6. The system model and simulation parameters in Fig. 6 are configured the same as in Fig. 5. Based on curves in Fig. 6, the normalized energy efficiency with the energy efficiency optimization scheme is larger than that with the conventional SINR scheme under different path loss factors. Figure 6 shows that the normalized average energy efficiency decreases with increased normalized intensity of user terminals, because the higher interference is conducive to lower capacity and lower energy efficiency.

The interference coordination and energy efficiency models originate from the proposed framework of mobile converged networks. Based on the different constraint metrics, the interference coordination model can be used for interference optimization, and the energy efficiency model can be used for energy optimization. Moreover, based on other resource optimization constraints in the framework of mobile converged networks, many models can be built for performance analysis.

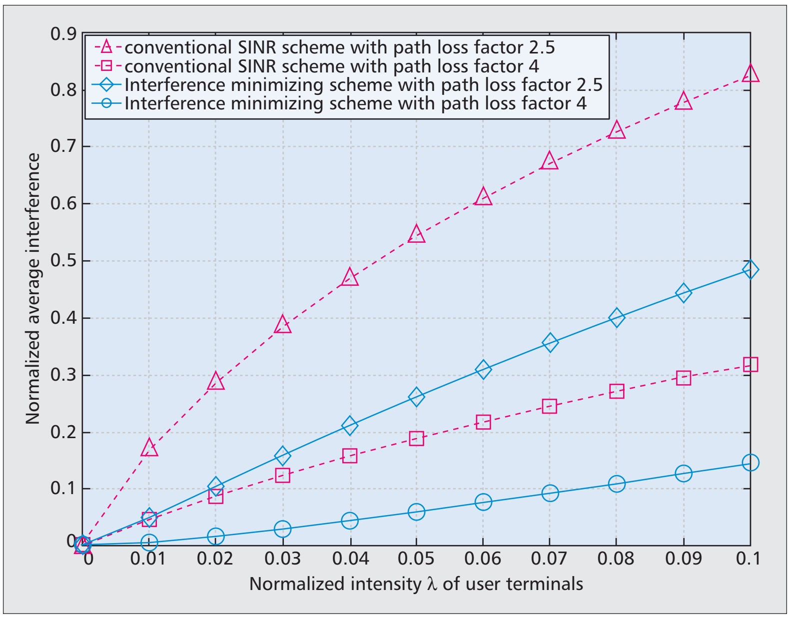

Figure 5. Normalized average interference of mobile converged networks with the interference minimizing and conventional SINR schemes.

Input initial configuration parameters in mobile converged networks, such as locations of nodes, transmission power, and resource allocation

Conflicting evaluation in frequency, spatial, and temporal domains of mobile converged networks;

While True **do**

  Evaluate conflicting distribution in multi-domains;

  Calculate the aggregated interference I_C;

  repeat

    $I_{OPT} \leftarrow I_C$

    Search the region with the maximal co-channel interference;

    Check the interference tolerance in every tier of wireless heterogeneous network, and then adjust the cross-tier routing into the tier of the network with the maximal interference tolerance;

    Evaluate the new conflicting distribution in frequency, spatial, and temporal domains;

    Calculate the new aggregated interference I_C;

  until $I_C \geq I_{OPT}$

  Revise the configuration parameters based on nodes mobility;

end while

Algorithm 1. The interference minimizing algorithm of mobile converged networks.

Future Challenges

It is always a great challenge to build a comprehensive system model of mobile converged networks to cover different types of characteristics in multi-tier wireless heterogeneous networks. Such a characteristic usually cannot be represented by a single system parameter. In addition, accuracy and effectiveness are equally important for a comprehensive system model; otherwise, the computational complexity of such a model will increase dramatically and cannot be tackled by typical performance evaluation approaches. Hence, what the key trade-offs between accuracy, effectiveness, and complexity are is an interesting question for future research. For a particular system model, there remain many open research issues, such as design and deployment of multi-tier network architecture, node position optimization, and resource optimization across multiple networks in the analysis of system performance under realistic network conditions.

Based on the proposed framework and comprehensive system model, new algorithms can be developed to improve the performance of mobile converged networks. Besides interference coordination and energy efficiency, different applications and user behaviors, such as audio/video streaming, interactive games, and online news, and the corresponding QoS provisioning and resource allocation will also affect the whole system performances. Therefore, new resource optimization algorithms considering throughput, delay, and link reliability should be further developed and analyzed accounting for different application types and scenarios.

Although there are some obstacles for operators and researchers to evaluating the performance of mobile converged networks considering the different standards and commerce security, this is not an excuse not to converge multi-tier wireless heterogeneous networks into a mobile converged network. To ensure this outcome, the standards of mobile converged networks measurement and estimation should be made a matter of regulation and enforcement by the regulatory authorities.

Conclusion

The convergence of different types of heterogeneous networks has become one of the main research directions in future wireless networks. In this article, we propose a new framework for mobile converged networks to cover different types of heterogeneous networks. A uniform framework for mobile converged networks would be helpful to design and evaluate performance in a single model. Furthermore, considering objectives of interference coordination and energy efficiency, two models of mobile converged networks and corresponding algorithms are developed. However, there are still many issues to converge different types of heterogeneous networks, such as modeling, resource optimization, and performance evaluation of mobile converged networks. If these are done, a veritable challenge would indeed emerge in the next round of the telecommunications revolution.

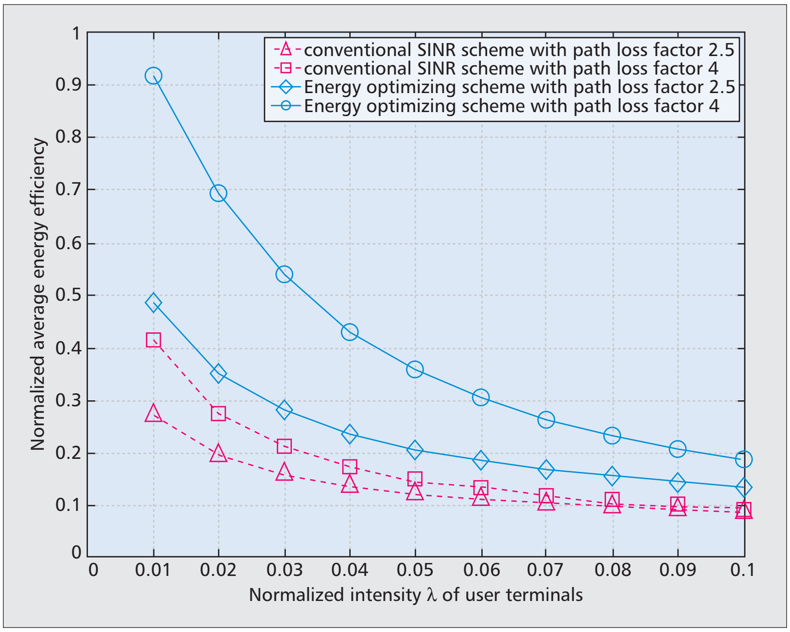

Figure 6. Normalized average energy efficiency of mobile converged networks with the energy-efficient and conventional SINR schemes.

1: Input initial configuration parameters in mobile converged networks, such as locations of nodes, transmission power, and resource allocation;

2: Calculate the energy efficiency and the network flow in frequency, spatial, and temporal dimensionalities of mobile converged networks;

3: **while** True **do**

4: Calculate the network flow F_C and the energy efficiency E_C;

5: **repeat**

6: $E_{OPT} \leftarrow E_C$

7: Search the minimal energy efficiency region in a mobile converged network;

8: Analyze the network flow in multi-tier heterogeneous networks and the corresponding energy efficiency;

9: Adjust the network flow by cross-tier routing algorithms to maximize the energy efficiency;

10: Calculate the new energy efficiency E_C in the specified region;

11: **until** $E_C \geq E_{OPT}$

12: Change the network topology based on the mobility of user terminals;

13: **end while**

Algorithm 2. The energy efficiency optimization algorithm of mobile converged networks.

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References

[1] D.-E. Meddour *et al.*, "Completing the Convergence Puzzle: A Surveyand a Roadmap," *IEEE Wireless Commun.*, vol. 16, no. 3, 2009, pp. 86–96.

[2] J. Zhang *et al.*, "Mobile Cellular Networks and Wireless Sensor Networks: Toward Convergence," *IEEE Commun. Mag.*, vol. 50, no. 3, 2012, pp. 164–69.

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[3] K. Han *et al.*, "Efficient Sensor Node Authentication in Third Generation-Wireless Sensor Networks Integrated Networks," *IET Commun.*, vol. 5, no. 12, 2011, pp. 1744–54.

[4] L. Shan, Z. Li, and H. Hu, "Converged Mobile Cellular Networks And Wireless Sensor Networks For Machine-to-Machine Communications," *KSII Trans. Internet and Info. Systems*, vol. 6, no. 1, 2012, pp. 147–61.

[5] J. Xiao *et al.*, "Energy-Efficient Data Collection in WSN-MCN Convergence Architecture," *Proc. IEEE 14th Int'l Conf. Commun. Technology '12*, Nov. 9–11, 2012, pp. 524–30.

[6] H. Gao *et al.*, "A QoS-Guaranteed Resource Scheduling Algorithm in High-Speed Mobile Convergence Network," *Proc. 2013 IEEE Wireless Commun. and Networking Conf. Wksps. '13*, Apr. 7–10, 2013, pp. 45–50.

[7] B. Bae *et al.*, "Hybrid DMB Services Based on Mobile Broadcast/Communication Converged Networks," *Proc. 8th IEEE Int'l. Symp. Broadband Multimedia Sys. and Broadcasting*, BMSB 2013, June 4–7, 2013, pp. 1–4.

[8] X. Yang and T. J. Owens, "Intersystem Soft Handover for Converged DVB-H and UMTS Networks," *IEEE Trans. Vehic. Tech*., vol. 57, no. 3, 2008, pp. 1887–98.

[9] T. Taleb and A. Ksentini, "Follow Me Cloud: Interworking Federated Clouds and Distributed Mobile Networks," *IEEE Network*, vol. 27, no. 5, 2013, pp. 12–19.

[10] P. Han *et al.*, "Network Selection in Heterogeneous Wireless Networks Using Learning Automata," *Proc. Int'l. Conf. Wireless Commun. and Signal Processing '12*, Oct. 25–27, 2012, pp. 1–6.

[11] D. Stoyan, W. S. Kendall, and J. Mecke, *Stochastic Geometry and Its Applications*, Wiley, 1995.

[12] B. Liang and Z. J. Haas, "Predictive Distance-Based Mobility Management for Multidimensional PCS Networks," *IEEE/ACM Trans. Networking*, vol. 11, no. 5, 2003, pp. 718–32.

[13] X. Ge *et al.*, "Spectrum and Energy Efficiency Evaluation of Two-Tier Femtocell Networks with Partially Open Channels," *IEEE Trans. Vehic. Tech*., vol. 63, no. 3, 2014, pp. 1306–19.

[14] L. Xiang et al., "Energy Efficiency Evaluation of Cellular Networks Based on Spatial Distributions of Traffic Load and Power Consumption," *IEEE Trans. Wireless Commun*., vol. 12, no. 3, 2013, pp. 961–73.

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