An Advanced Wi-Fi Data Service Platform Coupled with a Cellular Network for Future Wireless Access

Riichi Kudo, Yasushi Takatori, B. A. Hirantha Sithira Abeysekera, Yasuhiko Inoue, Atsushi Murase, Akira Yamada, Hiroto Yasuda, and Yukihiko Okumura

ABSTRACT

Wireless LAN devices are now everywhere because of the rapid spread of smart wireless devices. Demand for far richer content services is also driving the expansion of mobile traffic. Converging the cellular network with Wi-Fi is a reasonable way to support the increasing mobile traffic because most mobile user terminals already have Wi-Fi interfaces. More opportunities for Wi-Fi use require further enhancement of system capacity and manageability, especially in the high-density Wi-Fi network. This is because the chronic depletion of system resources is becoming a significant problem in the Wi-Fi network given the increases in Wi-Fi density and traffic. This article introduces a Wi-Fi data service platform coupled with cellular networks, which strengthens the synergy of two networks. Enhanced monitoring and performance prediction are essential to provide a high-grade user experience in high-density Wi-Fi environments.

INTRODUCTION

The proliferation of smart wireless devices such as smart phones and tablets has been rapidly increasing mobile traffic. Demand for far richer content services is depleting radio resources. These trends underlie the explosion in mobile traffic that has been observed in actual networks. It is predicted that the mobile traffic will explode 1000-fold in the next decade if the current trend of a two-fold traffic increase each year continues. Thus, it is crucial to increase system capacity and prepare for future wireless access systems in the upcoming tremendous mobile traffic era. Converging the cellular network with Wi-Fi is a reasonable way to support increasing mobile traffic because most mobile user terminals already have Wi-Fi interfaces [1, 2]. The latest Wi-Fi, 802.11ac, already offers a maximum physical layer data rate (PHY rate) of over 400 Mb/s in the 5 GHz band even for single antenna arrangements [3]. This makes Wi-Fi attractive as one of the user data planes in cellular systems. In the Third Generation Partnership Project (3GPP), the access network domain selection function (ANDSF) [4] defines how to switch between Wi-Fi and cellular access by exchanging policies, and such interworking with cellular systems is also accelerating the use of Wi-Fi.

Figure 1 shows the relationship between the three key performance factors of Wi-Fi in future wireless access systems. The first factor is operator/service provider performance; this includes the number of Wi-Fi services supported and the amount of Wi-Fi traffic. The second one is the proliferation of Wi-Fi systems. This factor is significant for vendors. The last one is user experience. The first flow indicates that the increase in Wi-Fi traffic will require more Wi-Fi deployments. In the second flow, the increase in Wi-Fi system density improves user experience. The improved user experience/satisfaction triggers the third flow, increases in the Wi-Fi traffic. More opportunities to access the Wi-Fi network will also fuel the creation of novel network services. The technological challenge is to support the second flow, that is, how to improve user experience with high-density Wi-Fi. This issue has been intensively discussed in the IEEE 802.11-HEW Study Group and has led to the formation of the IEEE 802.11 Task Group ax (TGax) that defines both physical (PHY) and medium access control (MAC) layers to achieve improvement in the average throughput per station in dense deployment scenarios [5]. Further enhancement can be expected by introducing Wi-Fi management over the entire network; the goal is to manage not only high-density Wi-Fi systems, but also traffic load balancing among Wi-Fi systems and cellular systems.

Toward this vision, it is essential to predict Wi-Fi performance in the complex radio environment where multiple Wi-Fi access points (APs) and various wireless systems contend for the same frequency resources. The extremely dense Wi-Fi deployment and huge mobile traffic will make the Wi-Fi throughput more unstable. In this article, we advocate the deployment of a converged network architecture wherein the Wi-Fi management architecture integrates Wi-Fi network management with the cellular network links. We first review Wi-Fi performance and

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\begin{cases} R = \dfrac{E[\text{successfully received payload information in total time } T]}{E[\text{time used for data symbols successfully received}]} \\ P = \dfrac{E[\text{time used for data symbols successfully received}]}{E[\text{total time } T]} \end{cases} \quad (1)
$$

describe what causes the throughput degradation in dense Wi-Fi deployment. The, we discuss the enhanced Wi-Fi radio environment monitoring and Wi-Fi performance prediction. In the following, the management of the Wi-Fi network and mobile traffic are discussed. Finally, we summarize how the positive circulation in Fig. 1 is accelerated by the described architecture.

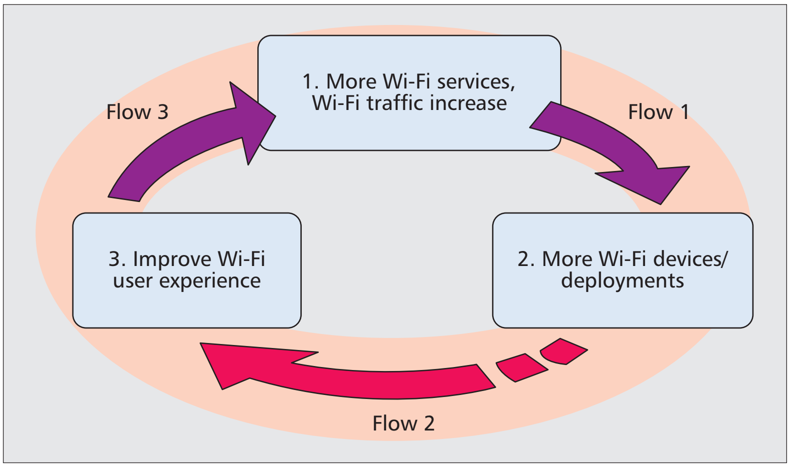

Figure 1. Positive cycle of Wi-Fi deployment.

Wi-Fi Performance in Future Wireless Access Systems

Future Wi-Fi is expected to be densely deployed and to overlay the cellular network. Effective utilization of Wi-Fi networks becomes more important to improve total mobile network capacity as well as user experience. Thus, performance estimation of wireless networks is necessary to manage network capacity and user experience. The current public/enterprise network uses a Wi-Fi access controller (AC); it improves Wi-Fi performance by managing radio resources and traffic loads among multiple APs. However, even the current AC faces difficulties in estimating Wi-Fi throughput in high-density Wi-Fi deployments because of the complex radio environment; each Wi-Fi works autonomously in unlicensed frequency bands. Wi-Fi throughput is expressed as the expectation of the payload information transmitted over total time T [6]. Total time T is the duration from when the payload information is enqueued to the receipt of an acknowledgment. Thus, Wi-Fi user throughput can be divided into PHY rate R and successful transmission ratio P as in Eq. 1, where $E[\cdot]$ denotes expectation. $R \times P$ denotes the Wi-Fi user throughput. The related factors are shown in Table 1. Estimating Wi-Fi throughput requires an assessment of all these factors. The PHY rate can be predicted more easily than successful transmission ratio P since the relating factors can be directly measured in the basic service set (BSS), which consists of a single AP and its associated UEs, and works as a basic block in Wi-Fi systems. The instability of P is mainly caused by coexistence with other BSSs and other wireless systems. The effects of the interference from such wireless systems must also be predicted to control Wi-Fi throughput.

OBSS

The influence of the overlapping BSS (OBSS) corresponds to the factors of resource sharing with other BSSs in the same channel, overlapping among multiple BSSs (exposed terminal problem) for transmission opportunity in the BSS, and overlapping among multiple Wi-Fi nodes (hidden terminal problem) for packet collision probability in Table 1. The factors are strongly related to the traffic of other BSSs, which can dynamically change. The hidden and exposed terminal problems are inherent to carrier sense multiple access with collision avoidance (CSMA/CA) protocols, and these problems are enhanced when the traffic of other BSSs occupies almost all radio resources. In the sparse traffic condition, the hidden terminal problem can be mitigated by using request to send/clear to send (RTS/CTS) handshake. This, however, becomes an imperfect solution in a heavy traffic environment since the RTS receiver cannot transmit CTS packets as it detects OBSS transmission. Furthermore, the current IEEE 802.11 wireless LAN standard does not have any solutions to the exposed terminal problem for unregulated dense AP deployment. The impact of the hidden and exposed terminal problems depends on the Wi-Fi link condition and their traffic. These problems degrade the transmission opportunity and/or increase the packet collision probability with the OBSS.

Inter-System Interference

The inter-system interference also influences the transmission opportunity and packet collision probability (Table 1). It is well known that several interference sources exist in the 2.4 GHz band (microwave ovens, Bluetooth, etc.). For instance, microwave ovens can degrade Wi-Fi performance but only at specified times and places. The 5 GHz band offers much greater allocatable bandwidth than the 2.4 GHz band. However, large parts of the 5 GHz band are shared with radar systems, and Wi-Fi systems must avoid interfering with them. Upon discovering an active radar, the AP must terminate the current data transmission, select a new channel, inform the impacted UEs, and move to the new channel. In the dense Wi-Fi and heavy traffic environment, such a drastic change in Wi-Fi traffic may cause large-scale disconnection. Furthermore, new systems using 5 GHz unlicensed band channels are being discussed in [7]. If such new systems become popular, the characteristic of inter-system interference must be analyzed to predict the influence of them.

Numerical Example

Figure 2 shows the cumulative distribution functions (CDF) of the Wi-Fi throughput for 200 UEs in a residential simulation scenario [8].The offered downlink traffic load for each UE was set to 5 Mb/s, 10 Mb/s, 20 Mb/s, 40 Mb/s, and 65 Mb/s to each user station (STA). Since each AP has two UEs, the load-PHY ratios, which are the ratios of load carried to the PHY rate, were 7.5 percent (= 5 [Mb/s] × 2 [UEs]/130 [Mb/s]), 15, 30, 60, and 100 percent. The Wi-Fi channel was randomly selected from among four frequency channels Ch. 36, Ch. 40, Ch. 44, and Ch. 48 included in the 5.15–5.25 GHz band; this corresponds to the condition wherein a 5 GHz radar system prevents any channel sharing. When the disadvantaged UEs are defined as those with throughput less than 5 Mb/s, it is found that the rate of the disadvantaged UEs increases as the load-PHY ratio increases. Even when the load-PHY ratio is 15 percent, UE throughput can fall to under 1 Mb/s. This shows that the Wi-Fi performance is degraded by allocation of excessive amounts of traffic. Since the PHY rate is fixed, the significant throughput instability is ascribed to ratio P. Figure 3 shows the links between the APs and UEs. The circles and white ellipses denote the APs and UEs. The lines between Wi-Fi nodes indicate that the nodes can hear each other's signals; that is, the signals exceed the clear channel assessment (CCA) threshold in the communication channel. It is found that large clusters with more than 20 APs are formed. The maximum number and average number of the detectable APs at each Wi-Fi node in this simulation are 13 and 7.2, respectively. In the actual Wi-Fi environment, other factors such as real-time rate adaptation and uplink traffic should also be taken into account. The wireless resource is more deeply depleted as the PHY rate decreases and uplink transmission increases, which worsens the Wi-Fi conditions.

R: PHY rate	Frequency bandwidth	Channel usage of the other systems Channel usage condition of other BSSs
	Modulation and coding scheme (MCS)	Received signal strength identification (RSSI) of the Wi-Fi link
		Spatial multiplexing condition in single-user/multiuser-MIMO
		Interference condition under carrier sense level
		Rate adaptation algorithm
P: successful transmission ratio	Transmission opportunity	DATA length of other nodes
		Resource sharing with other UEs in the same BSS
		Resource sharing with other UEs in the other BSS with the same channel (OBSS interference)
		Interference condition among multiple BSSs, that is, expose terminal problem (OBSS interference)
		Interference from other systems (inter-system interference)
		Channel changes (due to radar detection) (inter-system interference)
	Packet collision	Random access contention
		Interference condition among multiple Wi-Fi nodes, that is, hidden terminal problem (OBSS interference)
		Interference from other systems (inter-system interference)
	Packet error due to MCS mismatch	Bit error rate of the successfully transmitted packet
		Bit amount of a packet
	Payload information Efficiency	DATA length
		Control/management signal overhead
	Available backhaul capacity for Wi-Fi	Backhaul capacity
		Traffic condition of other communication systems sharing the same backhaul network

Table 1. Factors associated with Wi-Fi throughput.

Management Architecture

Instantaneous throughput degradation must be avoided for UEs that want constant throughput even in high-density Wi-Fi environments. To get Wi-Fi performance under control, we advocate the deployment of an enhanced Wi-Fi management architecture (Fig. 4). The key components are the management block, Wi-Fi network, destination UEs, data source, and cellular network. The red and black lines denote the control signal paths and user data paths. The Wi-Fi network and Wi-Fi traffic should be managed to maximize Wi-Fi system capacity and avoid Wi-Fi access failures. Wi-Fi network and traffic management are conducted by three functions in the management block. The monitoring database collects feedback from the APs and UEs via control signal paths. The APs' and UEs' feedback are obtained by way of backhaul lines and the control plane of the cellular systems, respectively. The Wi-Fi performance estimator uses the information in the monitoring database. The radio resource manager maintains the Wi-Fi network and controls the traffic using the control signal paths. The entities of the Wi-Fi network are APs, UE-MRs (mobile routers, MRs, or UEs using a tethering function). It is expected that some of the APs are controlled by the management block and have the function of monitoring the Wi-Fi radio environment. A UE-MR also acts as UE and AP because it supports the access of both cellular systems and Wi-Fi to the destination STA that has only Wi-Fi interfaces. The cellular network has various base transceiver stations (BTSs) for macrocells, small cells, and spot cells. The BTS can collect the feedback from the destination UEs and UE- MRs, and transfer the Wi-Fi setting signals to the UE-MRs. The last block is destination UEs that include the STAs with only Wi-Fi interfaces, and UEs that have both Wi-Fi and cellular interfaces. The management block monitors the Wi-Fi radio environment, estimates Wi-Fi performance, and conducts radio resource management. Then the effectiveness of the radio resource management is evaluated by monitoring. Cycling through these three management blocks keeps improving the user experience even in the face of drastic radio environment change.

Radio Environment Monitoring

Information on the radio environment will become more critical for the success of the future Wi-Fi platform. Thus, the environment monitoring function should be enhanced in order to collect Wi-Fi information from not only APs but also UEs. Monitoring by the UE has the advantage that the Wi-Fi radio environment is monitored regardless of Wi-Fi connection status. This architecture enables wide-area radio resource management corresponding to the coverage area of BTSs. The APs and UEs can collect not only the information of their Wi-Fi links, but also the control signals from the surrounding APs and the interference from Wi-Fi and other systems. The monitoring information related to the Wi-Fi link could include RSSI, PHY rate, frame length, and frame loss rate. Other monitoring information could be the number of active Wi-Fi devices operating on each frequency channel, their capability information, MAC addresses of the transmitter and desired receiver, network allocation vector (NAV) information for virtual carrier sensing, frame type and frame length information of MAC frames, and a noise histogram, which is defined in IEEE 802.11 TGk Amendment "Access Network Query Protocol (ANQP)" in IEEE 802.11 TGu. The detected information must be associated with the Wi-Fi device ID, such as a MAC address, to estimate the Wi-Fi performance.

It is expected that the UEs will also measure the user experience parameters (i.e., throughput and/or latency) and notify the measured values to the monitoring database. For Wi-Fi throughput assessment, PHY rate and successful transmission ratio should be measured to comprehend the radio environment in Wi-Fi systems. The measured successful transmission ratio can be compared to the estimated one at the Wi-Fi performance estimator. When there are gaps between the measured and estimated throughputs, the Wi-Fi performance estimator must be improved to reduce the gap. The throughput measurements will be conducted periodically or after radio resource management activity. Efficient throughput measurement must be studied to alleviate the load of the control signal paths.

Wi-Fi Performance Estimation

The Wi-Fi performance estimator evaluates the successful transmission ratio in addition to the PHY rate estimation. The former should be evaluated in two aspects: OBSS in Wi-Fi systems and inter-system interference from other systems. Since the impact of OBSS is strongly related to the Wi-Fi links (Fig. 3), the Wi-Fi performance estimator extracts link information from the information in the monitoring database. The successful transmission ratio can be evaluated from estimated Wi-Fi links and assumptions of the Wi-Fi load PHY ratios of the links. We show an example of successful transmission ratio evaluation based on the residence model [8]. The Wi-Fi performance estimator uses the perfect Wi-Fi link information and feasible traffic assumptions. Figure 5 shows the evaluated successful transmission ratio of a certain BSS corresponding to channel selection. It was assumed that there is only downlink transmission, and the load-PHY ratios of the other BSSs are randomly distributed between 0 to 100 percent, and the load-PHY ratio for the focused BSS was set to 100 percent. The Wi-Fi links in four available channels (Ch. 36–48) are also shown in Fig. 5. The number of other detected APs is two for all channels. However, the distributions of the successful transmission probabilities are different in each channel. The successful transmission ratio in Ch. 36 is greater than those in other channels. The 10 percent outage of the successful transmission probabilities is 0.43 in Ch. 36. If one UE communicates with the AP in Ch. 36 with a PHY rate of 54 Mb/s, the Wi-Fi throughput is expected to be greater than 22 Mb/s with a probability of 90 percent. On the other hand, the successful transmission ratio in Ch. 48 could be less than 0.1 percent. The accuracy of the performance evaluation can be improved by using uplink/downlink traffic models of the other BSSs. Since

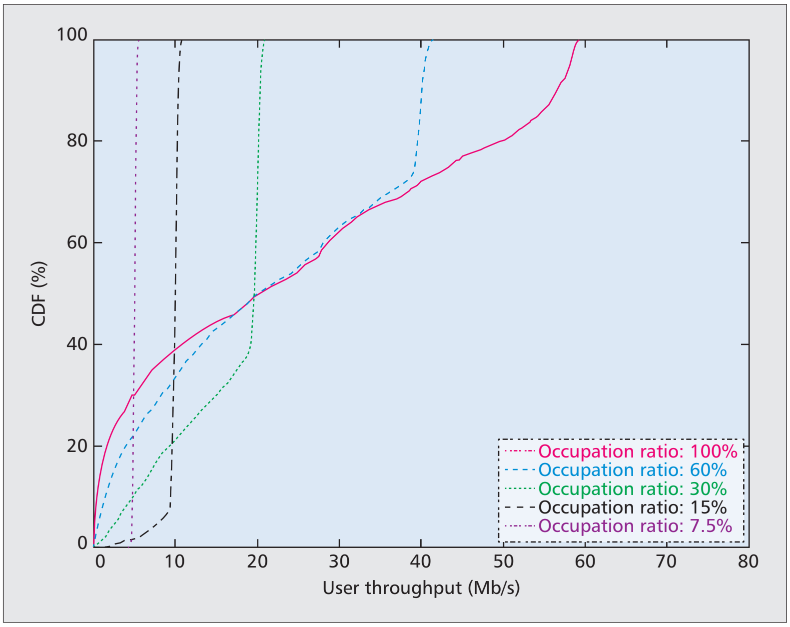

Figure 2. Numerical example of user throughputs. The PHY rate of the point-to-point transmission was set to 130 Mb/s (2 spatial streams, 64-QAM, 5/6 coding rate, 800 µs GI), transmission power of all Wi-Fi devices was set to 17 dBm, and only downlink transmission was considered. The building has 100 rooms each of which has one Wi-Fi AP and two UEs randomly located. The number of available channels is 4 by assuming the coexistence of a severe radar source.

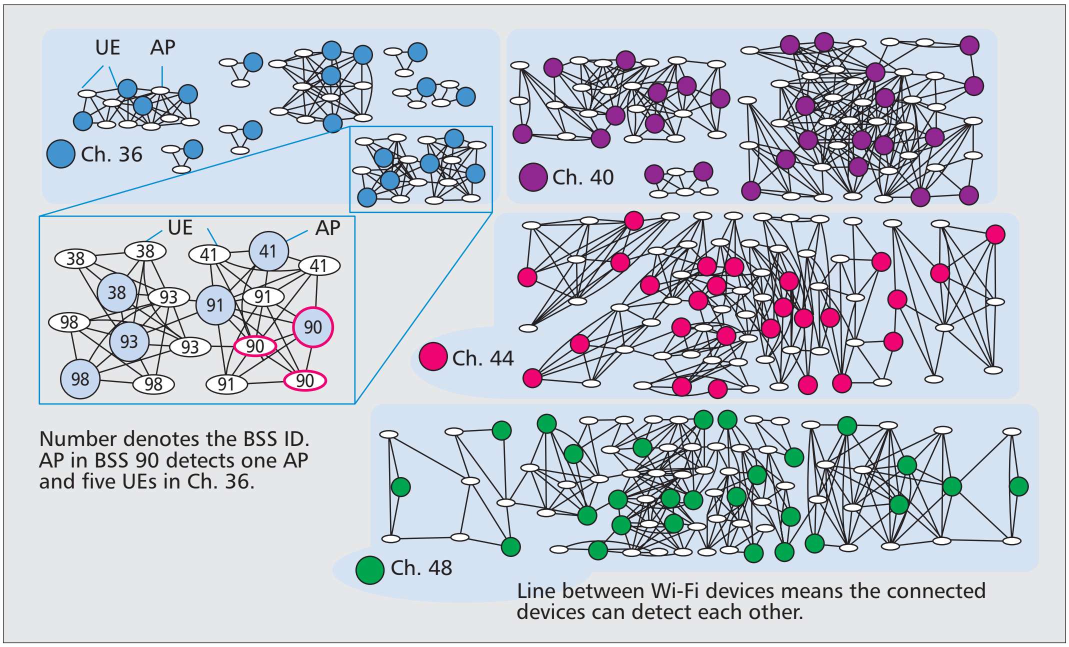

Figure 3. Wi-Fi links of a snapshot in the residence scenario simulations where the 100 APs randomly select their channels.

the traffic varies depending on the time or day, accurate traffic models improve the reliability of the successful transmission ratio. The calculation load of the successful transmission ratio evaluation can be reduced by simplifying the consideration of MAC layer operation. For example, the links that are likely to be affected by the hidden or exposed terminal problems can be identified by comparing IDs detected by Wi-Fi devices.

In addition to the static Wi-Fi links, the AP configuration changes, and the occasional Wi-Fi links caused by the UE-MRs also influence Wi-Fi performance. The Wi-Fi estimator needs to consider possible AP configurations. In the environment where the appearance of UE-MRs degrades the Wi-Fi performance significantly, feasible Wi-Fi links need to be considered in the successful transmission ratio evaluation. Thus, the Wi-Fi performance estimator prepares several possible Wi-Fi links to calculate Fig. 5.

The successful transmission ratio against the inter-system interference is also evaluated by using the monitored information. To evaluate the successful transmission ratio in a similar way to OBSS interference, the characteristics of the inter-system interference and detectable locations such as Wi-Fi links must be measured. For example, the incident rate of significant inter-system interference can be multiplied by the successful transmission ratio for OBSS interference. The Wi-Fi performance estimator analyzes the positions of detecting Wi-Fi devices, channels, and characteristics of the detected time. The actions of the APs that detect radar should also be analyzed in the 5 GHz band to evaluate the impact of the channel switching of the other APs. The influence of the channel switching of the other APs detecting radar can be evaluated as the successful transmission ratio against OBSS interference.

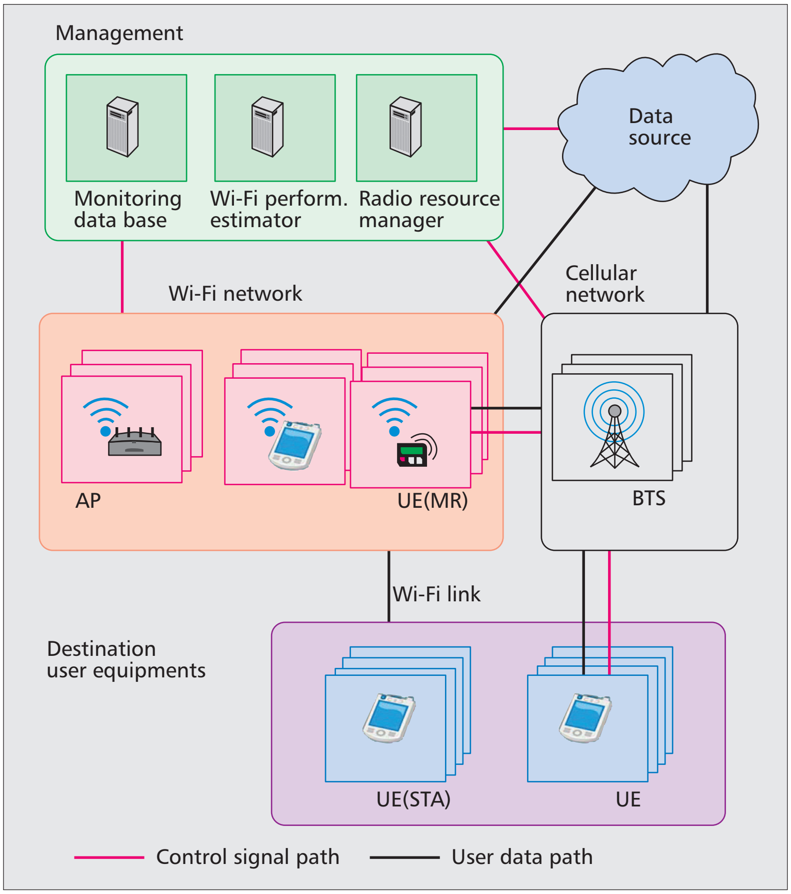

Figure 4. Wi-Fi management platform in the mobile network.

Radio Resource Management

The functions of the radio resource manager are AP configuration management and traffic management. AP configuration management determines the AP configuration parameters of APs and UE-MRs, and detects the abnormality in the Wi-Fi network to maximize and maintain Wi-Fi network capacity. To improve the successful transmission ratio, we need to analyze the transmission power, primary channel selection, channel aggregation use, contention window size, and RTS/CTS use. CCA threshold control is possible to develop to construct the adequate Wi-Fi links. Traffic management supports UE access selection or determines adequate UE access to avoid access failures caused by unstable Wi-Fi performance.

AP Configuration Management

The AP configuration is determined to improve the successful transmission ratio by considering possible parameters in the Wi-Fi performance estimator. When evaluating the successful transmission ratio as shown in Fig. 5, the AP configuration set the channel of the AP to Ch. 36. It is possible to choose the channel to maximize arbitrary percent outage or average data packet occupation ratios. Since the Wi-Fi radio environment information is enhanced by the monitoring via the control plane of the cellular network, the UE (STA) with only Wi-Fi interface also gains an advantage with radio resource management. If the monitoring database detects the radio environment reaction, a change in AP configurations of the surrounding APs after setting the AP configuration, the AP configuration management needs to consider the further AP configuration change corresponding to the changed radio environment. The timing of the AP configuration change must be also optimized by considering the load of the AP configuration change.

Since the Wi-Fi links shown in Fig. 3 impact Wi-Fi performance, it is possible for the AP configuration management to consider which links should be added or eliminated. The Wi-Fi links should be constructed to improve the successful transmission ratio. The position of an added AP can be roughly estimated from the results of radio environment monitoring at UEs and their position information. The Wi-Fi links created by UE-MRs should be managed by the AP configuration management to minimize the system capacity decrease created by the Wi-Fi link of UE-MRs. When the communication of the UE-MR decreases the Wi-Fi performance of some links, the radio resource management can reduce the cellular traffic of the UE-MR.

Traffic Control

The evaluated Wi-Fi performance can be used for traffic control to optimally share the mobile traffic among Wi-Fi and cellular network access. The wireless access of the UE with Wi-Fi interface must be determined from among Wi-Fi access, cellular access, and link aggregation with both. The access determination can be realized by three approaches: Wi-Fi performance information sharing, access policy distribution, and access designation notification. In performance information sharing, the evaluated Wi-Fi performance of the existing AP is reported to the UE. The UE can consider the user condition/preference, power saving mode, CPU and memory condition, application information, and cellular

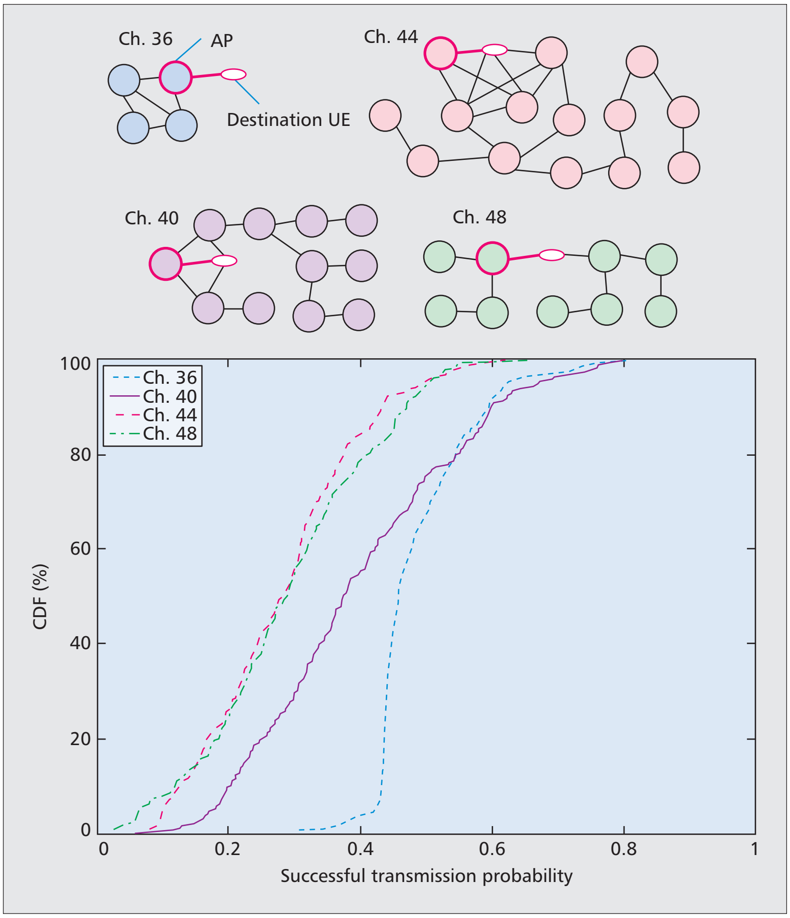

Figure 5. Cumulative distribution function of successful transmission probabilities of four available channels. It is assumed that the load-PHY ratios of the other BSSs are set to from 0 to 100 percent. Only downlink transmission using RTS/CTS exchanges is considered.

data traffic limit contract. Policy distribution yields a loosely coupled Wi-Fi/cellular network by using the performance evaluation in both Wi-Fi and cellular systems. The policy needs to be extended to support the distribution of the successful transmission ratio. In the final approach, the UE access is determined by the mobile , and the UE uses the designated access. In this approach, the UEs do not care which wireless access medium they are using. Since the Wi-Fi access failure must be avoided in order not to damage the user experience, robust Wi-Fi access and/or adaptive link aggregation are essential.

In the tremendous mobile traffic era, the radio resources of most wireless systems will approach complete depletion. Excessive offloading to a Wi-Fi network may collapse the Wi-Fi network. Smart integration of Wi-Fi and cellular systems is required. Link aggregation between Wi-Fi and cellular systems is one promising approach to use the Wi-Fi network without damaging the user experience. Link aggregation can be implemented by several schemes using common IP addresses in both Wi-Fi and cellular networks or multiple IP addresses (i.e., S2a mobility based on general packet radio service [GPRS] tunneling protocol [GTP] and WLAN access to the enhanced packet core [EPC] network via SaMOG or MPTCP) [9]. Since Wi-Fi through-

The user experience is expected to be well maintained by effectively combining the significant but erratic Wi-Fi capacity with the steady cellular throughput.

put can be unstable, it is important for mobile operators to minimize cellular traffic for link aggregation UEs based on the successful transmission ratio of the Wi-Fi link.

The probability distribution of the successful transmission ratio is useful in selecting Wi-Fi access, cellular access, or link aggregation. The probability of extremely low Wi-Fi throughput is a useful indicator of Wi-Fi throughput instability. The information on successful transmission ratio may enable traffic allocation that is suboptimal but avoids unexpected throughput degradation. The user experience is expected to be well maintained by effectively combining the significant but erratic Wi-Fi capacity with the steady cellular throughput.

Conclusion and Future Directions

It is expected that the interworking of Wi-Fi and cellular systems will more fully realize the potential of Wi-Fi systems. This article has investigated the Wi-Fi data service platform in future wireless access systems given the anticipation of huge mobile data traffic loads. It was shown that the actual throughput of Wi-Fi is unstable in dense Wi-Fi deployment scenarios with the huge mobile traffic due to the complex Wi-Fi radio environment and interference from other wireless systems in unlicensed frequency bands. A possible Wi-Fi management architecture was introduced to effectively utilize the potential capacity of Wi-Fi in the mobile network. Monitoring the radio environment at APs and UEs enables the Wi-Fi data service platform to estimate the successful transmission ratio by considering the OBSS influence and inter-system interference. It is expected to strengthen UE adoption of monitoring functions to achieve better access. The control plane in cellular systems gets rid of the Wi-Fi monitoring limitation and further improves the Wi-Fi radio environment information.

Extension of the architecture with the following three approaches has the potential to achieve further enhancement. The first approach is consideration of more wireless systems, including convergence with other wireless access in different frequency bands as well as coexistence with other wireless systems operated by different operators. The second one is coordination with backhaul/fronthaul networks. The bottleneck of backhaul/fronthaul networks is expected to be identified by total traffic monitoring, and the calculation resources can be distributed into various access networks and nodes. The third one is cross-layer optimization taking into account the suitable application layer structure for the network architecture described in this article.

The first approach, more wireless systems, requires performance evaluations of various wireless access schemes based on propagation models and use cases. Even if the throughput of a single wireless system is unstable, the combination of wireless accesses provides a high-grade user experience. To enable seamless wireless access, the values of the radio resources of the different wireless accesses must be assessed by considering the PHY rate and successful transmission ratio distribution. In addition, cooperation among multiple operators should be considered on frequency resource sharing. The game theoretic approach is a new way to analyze such scenarios from the viewpoint of the frequency resource management strategy [10].

The backhaul/fronthaul access networks can be a bottleneck as the aggregated throughput in the dense mobile UEs increases. The optimization of all traffic, including wired and wireless accesses, will be required to resolve the backhaul/fronthaul restriction. The analysis of the aggregated throughput and latency information is expected to clarify the impact of the backhaul/fronthaul capacities. High transmission capacity between a management server and UEs may realize the concept of network computing where calculation of resource offloading is achieved by distributing the calculations among various nodes (e.g., management server, AP/BTS, and mobile devices) in the total mobile network.

Cross-layer optimization is the key area to add value to future wireless access systems. Since the user can utilize multiple networks/links simultaneously, it may be good to divide an application service into multiple application modules that use different wireless accesses. Requirements (e.g., throughput and latency) for each application module are sent to the management server, and multiple rounds of network management per user are conducted to provide the suitable connection for the application service. This new approach will accelerate aggressive cross-layer optimization.

The extension with the three approaches described above requires large-scale optimization. Unfortunately, it makes it difficult to deterministically derive the optimum values for all controllable parameters. Application of machine-learning techniques may be the most practical way to obtain a quasi-optimum solution within a limited time because performance levels with various parameters for a Wi-Fi radio environment are stored at the management server and can utilize the information as big data. Furthermore, information that is not directly relevant to mobile traffic may enhance the performance estimation at the management server. For instance, information related to people's behavior at public events or in weather have the potential to improve the mobile traffic forecasts and thus enable better proactive offloading.

In the radio resource depletion condition, one-way offloading to a Wi-Fi network may damage user experience due to the throughput instability related to the inherent problems of the unlicensed band. We believe that the future Wi-Fi platform architecture for future wireless access systems will optimize traffic sharing between Wi-Fi and cellular networks, and enhance overall mobile network performance. The synergy of the two networks will further strengthen the positive circle shown in Fig. 1.

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We believe that the advanced Wi-Fi platform architecture for future wireless access systems will optimize the traffic sharing between the Wi-Fi and cellular networks and enhance the overall mobile network performance.