# Channel Width Adaptation and Access in High-density WiFi Networks

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## Abstract

WiFi will be an important choice to load off the ever increasing data demand of end users in future mobile converged networks, which will inevitably result in high-density WiFi deployments. However, higher density of WiFi networks is not a guarantee to obtain higher throughput, because of the increasing interference among end users and overlapped WiFi networks. As a solution to this problem, this research proposes a flexible framework for fine-grained channel width adaptation and multi-channel access in WiFi networks. The framework adopts DOFDM (Discontinuous Orthogonal Frequency Division Multiplexing) in physical layer, which allocates the frequency resource in the granularity of sub-carrier. And in MAC layer, it uses a frequency-time domain backoff scheme to decrease the access collision, resulting in higher access probability for the contending nodes.

## 1. Introduction

With the ever increasing of mobile terminals and the killer applications, such as visual telephone and high-definition video streams, the demand for high-throughput wireless networks is highly increased. Although in recent years, the infrastructures in 3G and 4G mobile networks have been greatly enhanced, the cellular network only can not meet this demand. Among other choices, WiFi may be the most popular one to load off traffic from traditional cellular networks, since it is easy to deploy, low-costly to manage and can cover a wide area. And therefore, more and more WiFi APs are deployed around us nowadays. However, more WiFi APs is not a guarantee for end users to obtain higher throughput, because of the increasing interference among both end users and overlapped WiFi networks. The intense contention to the shared spectrum resources, resulting in collision and backoff process, will badly decrease the network efficiency. In particular, with modern communication technologies are steadily advancing the physical layer (PHY) data rates, this network efficiency is more urgent to address. For example, the network efficiency in an 802.11n network at 300Mbps is only around 20%[1].

The fundamental reason for this inefficiency is that the current Media Access Control (MAC) allocates the entire channel to one node, which means that even if a node has a small amount of data to send it still needs to contend for the entire channel. And the time for contention resolution, which usually uses the basic and lower transmission rate, prior to the data transmission is therefore an overhead, resulting in that the higher the PHY data rate the lower the throughput efficiency will become. Channel width adaptation technique is a promising solution to this problem. It slips one big channel into several small channels for different users that simultaneously have data to transmit, or aggregates several small channels into one big channel for one user with high throughput requirement. Channel width adaptation promises to increase the throughput for end users and the network efficiency at the same time, and it is taken as the necessary technique in the future wireless networks.

## 2. Related work and motivations

In 2008, Chandra and Bahl [2] used only commodity 802.11 hardware to communicate at different channel width of 5, 10, 20 and 40 MHz, and first quantify the impact of channel width on throughput, range, and power consumption. It shows that channel adaptation can lead to significant improvements in many of the desirable metrics in wireless networks: range and connectivity, battery power-consumption, and capacity. And driven by the benefits of adapting channel width according to different network scenario, IEEE 802.11n standard [3] has already been enhanced by a simple channel aggregation technique. It allows end users to aggregate two adjacent 20 MHz channels into one 40MHz channel at the spectrum band of 5GHz U-NII. The main objective of this enhancement is to support high-throughput traffic. Besides high-throughput, in order to increase network efficiency in high-density WLAN, Kun Tan, etal. [4], introduce a method named FICA that can allocate the spectrum resource at a thinner granularity. It utilizes OFDM

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technique to divide a whole channel into orthogonal sub-channels. It is shown that FICA can improve the efficiency by up to 400% compared to existing 802.11. But in FICA, the sub-channels are still divided equally each time. Similarly work are designed and implemented in Jello [5], Picasso [6] and WiFi-NC [7]. They all utilize spectrum fragmentation, or channel slicing based on OFDM or OFDMA, that can slice each device's channel into separated sub-channels and thus can support concurrent and interference-free transmission over these sub-channels. The most recent work in [8] enables the operation of channel width adaptation in a more elaborate way, that it allows the users to adapt channel width in the frequency of once per packet. From 2009 on, we also make effort in the research on multi-channel access and channel width adaptation. We propose a cooperative multi-channel MAC [9] and a flexible framework for fine-grained multi-channel access scheme in WLAN [10].

The channel width adaptation is shown to highly increase the network efficiency, and inevitably make the available spectrum into multiple channels. Although the multi-channel MACs have been extensively researched [11], most of them assume that each channel with equal bandwidth. In practice, there exists a gap between the fine-grained channel width adaptation in PHY layer and the multi-channel dynamic access in MAC layer. In this research, we propose a framework inspired by recent research activities, and it advances this research field in the following aspects. (i) The framework adopts DOFDM for width channel adaptation that can fully utilize the sparse separated spectrum resource, and it can also be easily realized in OFDM-based systems. (ii) The framework can adapt channel width at the granularity of sub-carriers, and allows multiple channels for concurrent communication be of different width, which brings more flexibility in high-density wireless networks. (iii) The framework utilizes a combined frequency domain and time domain backoff process, which can decrease the access collision, resulting in higher access probability and less access delay for the contending nodes.

## 3. Cross-layer framework

### 3.1 DOFDM for fine-grained channel width adaptation

The basic idea of the channel width adaptation is that we can use variable numbers of sub-carriers, whether they are adjacent or not, to compose a channel without changing the framework of OFDM systems (as illustrated in Fig. 1). This can be easily implemented in existing techniques, since OFDM has been embraced by many existing wireless standards like IEEE 802.11a/g/n and WiMax. Supposing the FFT size in the OFDM modulation is N, and the total available frequency bandwidth is B. Then the bandwidth of each sub-carrier in theory is B/N. The framework information of the OFDM, i.e, B and N, is known to the AP and mobile terminals. To emphasize that it can aggregate discontinuous sub-carries into one channel, we refer to this as Discontinuous-OFDM (DOFDM). The benefit of DOFDM is twofold, first it can increase the frequency diversity, and second, it can utilize the sparse spectrum resource under the intense contention status in high-density WiFi networks.

We consider the uplink where end users transmitting data to the AP, while downlink access will follow the same process as uplink with roles reversed. One whole transmission procedure is divided into two phases, i.e. control phase and data exchange phase. During the control phase, through RTS/CTS handshake, all nodes attempt to make agreements for sub-carriers to be used during the following data exchange phase. And in the data exchange phase, the user nodes aggregate the assigned sub-carriers into one sub-channel for data transmission. One whole data transmission procedure is illustrated in Fig. 2. Note that a sub-channel can be composed by dis-adjacent sub-carriers, but in Fig. 2 we only illustrate the case that all sub-channels (i.e., CH *1*, CH *2*, …, and CH $M_{CH}$) are composed by adjacent sub-carriers only for convenience.

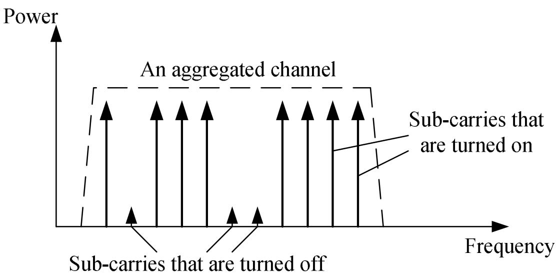

Fig. 1. Channel adaptation using DOFDM

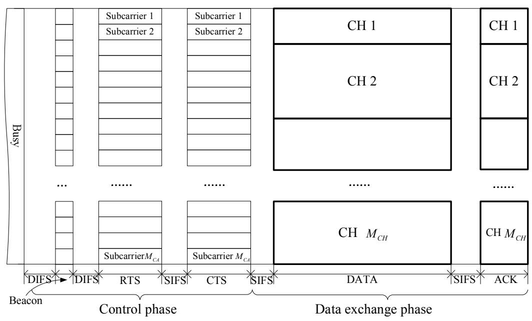

Fig. 2. One successful data transmission procedure

### 3.2 Packets sequence in MAC layer

Any node has data to transmit will randomly select a number of sub-carriers to send its requirement on the amount of sub-carriers to the AP in the RTS period, based on their respective traffic load. After successfully receiving the RTS's from each node, AP will allocate the sub-carriers to the user nodes in the CTS period. The allocation information, includes the IDs of the allocated sub-carriers, will be enclosed in the sub-carriers that respectively selected by each user node in the RTS period.

If a node successfully receives the sub-carrier allocation information, it will aggregate the allocated sub-carriers as one sub-channel to transmit DATA package to the AP. After successfully receiving the DATA packets, the AP will feedback ACKs to the transmitters using the same sub-channel as DATA packets respectively. And the nodes that fail to receive the ACKs from the AP will start a retransmission procedure in the next transmission procedure. On the other hand, if a node has not obtained the acknowledgment of its requested sub-carriers during CTS period, it will perform a backoff process as explained below.

## 3.3 Frequency-time domain backoff

There are two conditions that a node fails to obtain the acknowledgment of its request on sub-carriers. First, the RTS has not reached AP because of either collision or physical failure. Second, the RTS has been successfully received by AP, but AP has no more sub-carriers available for the requesting node because of saturation. We introduce a combination of frequency domain and time domain backoff process to tackle these two different conditions. In the first condition, whether due to collision or physical failure, a node will randomly select a sub-carrier other than the one used last time to send RTS and thus can reduce the chance of collision or physical failure again. In the second condition, we use time domain backoff by emulating the behavior of binary exponential backoff used in 802.11[12]. By this method, the number of contending nodes can be reduced in the next transmission procedure, and hence alleviate saturation.

Differentiating the collision or physical failure from saturation: AP is aware of saturation, i.e., when the RTS from a node has been successfully received by AP but AP has no more sub-carriers available for this requesting node, and AP will inform this situation to the suffering nodes. Otherwise, without receiving CTS or saturation information from AP, a node concludes that its RTS has not reached AP because of either collision or physical failure.

## 3.4 Sub-carrier allocation and negotiation

If the user nodes have different priorities, sub-carrier allocation will satisfy the user nodes in order of their priority. For the nodes that have the same priority, if the total amount of the requested sub-carriers is no more than the available amount, all the requirements can be satisfied and AP will allocate the same number of sub-carriers as the nodes' request. Otherwise, AP will have to choose its allocation strategy depending on the network scenario, for instance to first satisfy the nodes that request more sub-carriers in order to guarantee the access of nodes with more data to transmission, or to first satisfy the nodes with the smaller request in order to admit as many nodes as possible, or allocate the sub-carriers to all contending nodes pro to their respective requirements for fairness.

Another interesting thing is that considering the adaptation of users' QoS as well as the adoption of adaptive coding and modulation (ACM) technique [13], the amount of the sub-carriers that required by each node can be a range, for instance between $S_{min}$ and $S_{max}$, instead of a fixed number. In this case, the AP will first try to guarantee the basic requirement of $S_{min}$, and if it has more sub-carriers it can then update the service to this node by allocating it up to $S_{max}$ sub-carriers. The settings of $S_{min}$ and $S_{max}$ give the system more flexibility to use the frequency resource.

## 4. Performance evaluation

We first validate the throughput performance of our proposed framework by NS2 simulator. We consider a wireless network where contending users are randomly deployed in the area of 250m×250m and the AP is located in the center. The packet length subjects to uniformly distribution between 128 and 2048 bytes, and the total PHY data rate is 80Mbps. Fig. 3 shows the saturated aggregate throughput varying with different numbers of contending users, under the cases that we divide the total bandwidth into 4, 8 or 32 sub-channels during the control phase. The figure indicates the tradeoff as explained above, namely in general higher density of the network prefers to more sub-channels. Moreover, the throughput efficiency can reach up to 70% under the simulated scenarios.

We then validate the efficiency increase of the proposal comparing to FICA. And for fair comparison, the proposed framework adopts similar OFDM parameters to FICA, i.e., 256 sub-carries for 16 sub-channels, which means in FICA there are 16 sub-carriers in each sub-channel. The requirement of each node is randomly selected from 1 to 16 (in practice, a node may request for more than 16 sub-carriers, and then it will contend for more than one sub-channels in FICA). And we change the number of contending nodes to change the network load and create both scenarios when the request on sub-carrier is less and more than the available sub-carriers. With 1000 times Monte Carlo simulation, we compare the proposed scheme with FICA as plotted in Fig. 4. We can see that the proposed scheme can bring higher frequency efficiency in terms of both allocation ratio and utilization ratio, this is because that on one hand the nodes are contending through sub-carriers instead of sub-channels and thus has less chance to collide, and on the other hand, it allocates the frequency resource in the granularity of sub-carrier and can adapt the sub-channel width more fine-grained according to each node's request.

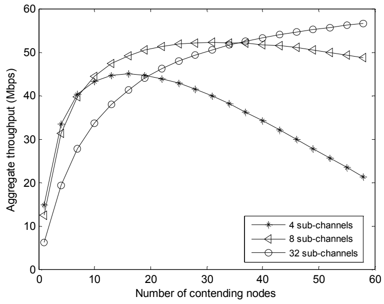

Fig. 3. The saturated aggregate throughput

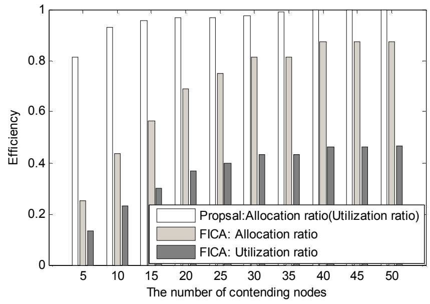

Fig. 4. Comparing the proposal with FICA in network efficiency

## 5. Conclusion

We present a cross-layer framework for fine-grained channel width adaptation and multi-channel access for high-density WiFi in mobile converged networks. It allocates the frequency resource in the granularity of sub-carrier and thus brings more flexibility to the network and higher frequency utilization efficiency than those in the granularity of sub-channel. This sub-carrier-granularity framework also facilitates the channel width adaptation in wireless network. And the combination of time-domain backoff the frequency-domain backoff in the framework can evidently decrease the access collision, resulting in higher access probability for the contending nodes. We believe this flexible framework will play a role in the future high-density, high-throughput and high-efficiency wireless networks.

## 6. Acknowledgments

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