FC-MAC: Fine-grained Cognitive MAC for Wireless Video Streaming

Lu Wang[*], Jiang Xiao[*], Xiaoke Qi[†], Kaishun Wu[*] and Mounir Hamdi[*]
[*]Department of Computer Science and Engineering, Hong Kong University of Science and Technology
[†]Institute of Automation, Chinese Academy of Sciences
[‡]Department of Computer Science, Shenzhen University

Abstract—**Recently, there is a massive growth in the amount of wireless video traffics. To increase the network efficiency and cater to the needs of Quality of Experience (QoE), researchers propose hybrid MAC schemes, with multiple MAC protocols anchored in a single MAC layer. Different MAC protocols are selected for diverse users' requirements. However, the existing hybrid MAC mainly combines various MAC protocols in time domain. Only one type of traffic can be satisfied at a time, and others have to endure poor QoE. Meanwhile, the channel resources are not fully utilized due to coarse usage in time domain. Motivated by this, we propose FC-MAC, a Fine-grained Cognitive MAC for video streaming in wireless networks. Instead of dividing channel time into slots, FC-MAC splits the channel frequency into fine-grained subchannels, and hybrid different MAC protocols in frequency domain. By dynamically adjusting the bandwidth and the MAC protocols according to the users' needs and channel condition, FC-MAC ensures the QoE at low cost and achieves high multiplexing gain. We conduct extensive simulations to verify the effectiveness of FC-MAC. Numerous results show that compared with time domain hybrid MAC, FC-MAC achieves 190% performance gain.**

I. INTRODUCTION

Recently, wireless video traffic becomes closely and indispensably related to our daily lives, such as delivering YouTube to smartphone, or broadcasting blu-ray signals around home. The bandwidth required for video streaming is usually one or two orders of magnitude more than that for other IP services, making it a significant driver of network traffic [1]. On the other hand, as the limited wireless spectrum usage becomes scarce, it is extremely challenging to cater to the needs of various video quality of experience (QoE) [2] [3]. Therefore, the wireless network design for video streaming calls for a breakthrough.

To increase the network efficiency and ensure the stringent QoE for video streaming applications, researchers consider to combine a set of MAC protocols into a single layer to meet the heterogeneous requirements from different users. In [4], a hybrid MAC named meta-MAC protocol is proposed. Meta-MAC dynamically selects the "best" MAC protocol from the protocol stack according to the local feedbacks. Another hybrid MAC, Z-MAC is presented in [5] for sensor networks. Z-MAC use carrier sense multiple access (CSMA) as the baseline MAC scheme, and dynamically adapt the duration of time division multiple acess (TDMA) according to the contention level. In [6], the authors analyze the performance of resource reservation-based MAC (TDMA) and contention-based MAC (CSMA), and propose hybrid MAC to fit the WiMedia UWB MAC super-frame efficiently.

As wireless multicarrier techniques become prevailing, frequency diversity brings in new challenges and opportunities for MAC protocol design [7]. To see why this happens, we take Orthogonal Frequency Division Multiplexing (OFDM) modulation as illustration. OFDM modulation transforms a frequency-selective wideband channel into several flat-fading narrowband subchannels supported by subcarriers. In this way, it is able to fight against multipath fading and increase the spectral efficiency. Meanwhile, the signals carried by different subcarriers experience quite diverse transmission quality, which is also termed frequency diversity. This diversity is well-known to be an additional dimension to exploit for wireless design, and it has been leveraged to facilitate numerous applications already [8].

We argue that the state-of-art the hybrid MAC protocols all concentrated in time domain. They primarily split channel into multiple time slots and run each kind of MAC at a time. Therefore, they are not capable of harnessing frequency diversity to improve the channel utilization. Moreover, when there are diverse transmission demands for video streaming, time domain hybrid MAC cannot meet all the requirements. Motivated by this, we propose a Fine-grained Cognitive MAC (FC-MAC) for video streaming in wireless networks. Unlike traditional time domain hybrid MAC (T-MAC) that divides channel time into multiple slots, and runs different MAC protocols one at a time, FC-MAC splits the channel frequency into fine-grained subchannels based on OFDM modulation, and hybrid a variety of MAC protocols currently on each subchannel. Through lightweight feedbacks, the access point(AP) can dynamically adjust the MAC protocol and bandwidth according to the frequency diversity as well as the traffic types of each client.

To the best of knowledge, FC-MAC is the first work of this kind in the literature that leverages frequency diversity to hybrid the MAC protocols in frequency domain. Our experiments show that compared with time domain hybrid MAC (T-MAC), FC-MAC achieves 190% performance gain, which demonstrate that hybrid MAC in frequency domain makes he spectrum usage more adaptively and efficiently, and thus benefits the heterogenous transmissions in wireless video streaming.

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II. RELATED WORK

The design of FC-MAC builds upon research in two previously unrelated areas of wireless: hybrid MAC protocol to ensure the QoE and harnessing frequency diversity to benefit multicarrier communication systems.

A. *Hybrid MAC Protocols*

Video streaming plays an more and more important role to consume media content in the last two decades. Yet as the bandwidth required for video streaming stresses the scarce spectrum, it is critical to ensure the QoE for the heterogeneous applications. Hybrid MAC protocols are conceived to relief this stress and increase the channel efficiency. The authors in [4] present a hybrid MAC named meta-MAC protocol, which dynamically selects the "best" MAC protocol from the protocol stack according to the local feedbacks. In [9], the authors explore the mechanism to adapt the MAC behavior between TDMA and CSMA according to the level of contention. This attempt combines the strengths of TDMA and CSMA while offsetting their weaknesses. Similarly, the authors in [6] analyze the performance of resource reservation-based MAC (TDMA) and contention-based MAC (CSMA), and propose hybrid MAC to fit the WiMedia UWB MAC super-frame efficiently. Another series of hybrid MACs, S-MAC [10], T-MAC [11] and Z-MAC [5] are proposed in sensor networks to achieve high channel utilization even under high contention. While our proposed FC-MAC shares the same goal with the previous hybrid MAC, it differs in the way that it hybrids the MAC protocols in frequency domain, and jointly consider the frequency diversity to meet the heterogeneous traffic demands for wireless video streaming.

B. *Harnessing Frequency Diversity*

Recently, OFDM techniques become an increasingly popular way to deliver wireless data. It leverage multiple orthogonal subcarriers in order to provide high data throughput. The RF signal transmitted over multiple subcarrier is affected by frequency-selective fading, and thus reveals diverse feature across a whole channel. Numerous research has been conducted to leverage such frequency diversity, like WLAN-based indoor localization [12], motion detection [13], rate adaptation [8], etc. In [14], adaptive OFDM modulation is proposed to increase the data rate by adjusting transmission parameter on subchannel level. In [8], the authors analyze the variation of Signal to Noise Ratio (SNR) on different subcarriers measured by Channel State Information (CSI), and propose several methods to harness frequency diversity. However, none of the above works leverage frequency diversity to benefit hybrid MAC protocols, which is the main focus of our paper.

III. FREQUENCY DOMAIN HYBRID MAC (FC-MAC)

In this section, we describe the overall architecture of a FC-MAC enabled communication system, which aims at harnessing frequency diversity to achieve hybrid MAC for wireless video streaming.

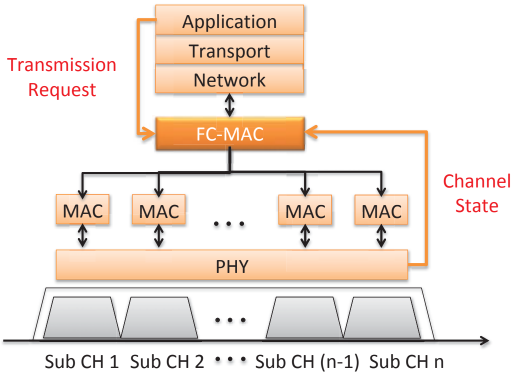

Fig. 1: The protocol stack of FC-MAC. It takes advantage of frequency diversity to hybrid MAC protocols in frequency domain. The MAC allocation depends on two metrics: transmission requests and subchannel condition.

A. *FC-MAC Overview*

The design of FC-MAC is initiated by two observations. First, PHY layer characteristics have certain impact on the performance of MAC protocols. It is proved that reservation based MAC introduces smaller distortion under higher signal to noise ratio (SNR) for signal reconstruction, and contention based MAC introduce smaller distortion under lower SNR for signal reconstruction [15]. What is more, when the channel condition is relatively good, reservation based MAC is better to fully utilize the channel resource, since there is hardly any diversity to exploit. While when the channel condition is relatively poor, contention based MAC is more adaptive and flexible. Second, video traffic characteristics also have certain preference for diffident kinds of MAC protocols. For instance, the reservation based MAC protocols can provide better support for real-time traffic with constant bit-rate (CBR), since they have a lower degree of collision. Conversely, the contention based MAC protocols are more suitable for bursty traffic with variable bit-rate (VBR) due to their flexibility.

Based on the above observations, we propose FC-MAC, a cross-layer design for wireless video streaming. FC-MAC is built on top of OFDM modulation, which enables fine-grained hybrid MAC in high-rate wide-band wireless local area networks (WLANs). For the sake of clarity, we list two necessary assumptions as follows: 1) currently we consider a scenario that consists of a single AP and multiple clients. The topology is a sparse to medium network with maximum number of clients $L = 15$ [7]; 2) the clients get implicit synchronized as in [7];

With the assumptions in mind, the fundamental idea of FC-MAC is to *leverage frequency diversity to achieve a more fine-grained hybrid MAC protocol for video streaming*. Fig. 1 demonstrates the protocol stack of FC-MAC. The entire channel is split into several subchannels, and each subchannel runs one type of MAC protocol. The AP has a FC-MAC layer that runs on top of each fine-grained MAC layers, which is in charge of subchannel and MAC allocation for each client.

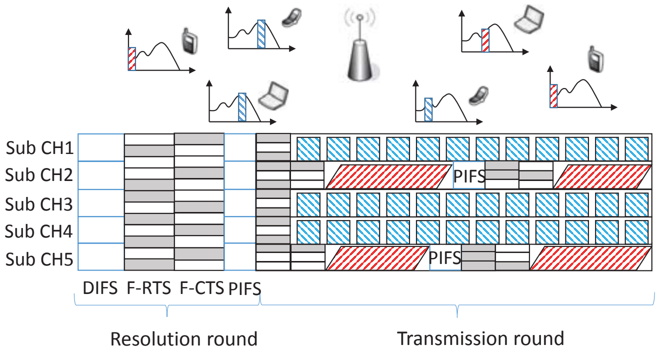

Fig. 2: An illustrated example of the time flow in FC-MAC with two types of MAC protocols. The entire channel is divided into 5 subchannels. Each subchannel runs one type of MAC protocol assigned by the AP.

By dynamically adjust the MAC protocol and subchannel according to the frequency diversity and the users' needs, FC-MAC aims to improve the channel utilization and ensure the QoE.

B. PHY Layer Architecture

To enable fine-grained hybrid MAC, the basic access unit in FC-MAC is subchannel, each contains a number of OFDM subcarriers. Normally in a 20MHz wide-band channel, every 16 subcarriers are grouped into one subchannel, with a bandwidth of 1.33MHz. The subcarriers are not necessarily contiguous, and the bandwidth can also be adjusted according to the system requirement. In fact, the subchannel is formed according to two principles: 1) it cannot be too narrow to degrade the transmission qualify, and 2) it cannot be too wide to waste the frequency diversity. Each subchannel runs one type of MAC protocols. The AP is in charge of the assignment based on two criteria: transmission request and channel condition. Here we adopt a frequency domain contention scheme. Unlike the traditional time domain contention, the transmission requests from all the clients are conducted concurrently in frequency domain. In this way, collision can be avoided, and resolution overhead can be reduced significantly.

FC-MAC abstracts the basic idea of PHY layer signalling for frequency domain contention, in terms of F-RTS/F-CTS [16]. Instead of transmitting RTS/CTS packets on subcarriers, binary amplitude modulation (BAM) are adopted to transmit the contention and resolution messages. BAM modulates binary numbers "0" and "1" using on-off keying. To demodulate the BAM symbols, a simple but efficient method is energy detection. Whenever the energy on a subcarrier exceeds a certain threshold, the BAM symbol is "1", otherwise it is "0".

FC-MAC contains two levels of F-RTS/F-CTS for wide-band access and subchannel access respectively. As shown in Fig. 2, during resolution round, F-RTS/F-CTS are used to allocate the subchannels as well as the MAC protocol run on them. While during transmission round, F-CTS in reservation based MAC is to arrange the transmission schedule, and F-RTS/F-CTS in contention based MAC are to obtain the access right to that subchannel. Thus they have different formats.

TABLE I: F-RTS/F-CTS format in resolution round

F-RTS	Tag band 16	Contention band 16	
		Transmission type 4	Bandwidth 16
F-CTS	Tag band 16	Resolution band 16	
		MAC type 4	Subchannel 16

In contetion/resolution round, F-RTS/CTS symbols consist of two components: tag band and contention/resolution band. Tag band is used to differentiate F-RTS and F-CTS. It locates at the beginning of the F-RTS/F-CTS symbol with 16 subcarriers. During the network initialization, each client is allocated 16 subcarriers as its contention/resolution band. For contention band, each client uses 4 subcarriers to declare the transmission type, and 12 subcarriers to specify the bandwidth in need. Similarly, the resolution band is also divided into two parts by the AP, where 4 subcarriers are used to state the MAC protocol and the rest are to declare the subchannels that can be used by the client. If the resolution band is not enough for subchannel declaration, another one or more F-CTSs are transmitted until the allocation is finished. Table I describes a possible format of F-RTS/F-CTS in resolution round.

In transmission round, reservation based MAC utilizes F-CTS to arrange the transmission schedule, while contention based MAC protocols adopt F-RTS/F-CTS for a fine-grained frequency domain contention, yet with totally different formats. That is because right now the only target is to obtain the access right. Thus F-RTS has a quite simple structure. Each client randomly picks up a subcarrier within the subchannel as its contention number, and transmits a BAM symbol on that subcarrier in F-RTS. Upon receiving all the contention numbers, the AP will randomly choose one and reply it in F-CTS. The client with that specific number then gains the channel access and conducts transmission right away.

Fig. 2 illustrates the timing in FC-MAC. The entire channel is divided into 5 subchannels. When the channel is idle for DIFS (DCF Interframe Space), the clients declare their transmission requests through F-RTS. Upon receiving the requests, the AP executes an QoE-enured MAC/subchannel allocation algorithm and replies the results in F-CTS. After wait for PIFS (PCF Interframe Space), the AP and clients start transmission on the corresponding subchannels. To communicate concurrently with different clients using various MACs, the AP adopts band-pass filter to separate the signals from each subchannels. Fig. 3 describes the downlink transmission procedure in FC-MAC. Similarity, during uplink transmission, the clients use band-pass filter to selectively remove all the signals except for the subchannel of interest.

C. MAC Layer Design

There are several aspects that influence the QoE, such as throughput, service latency and delay variation (jitter). To

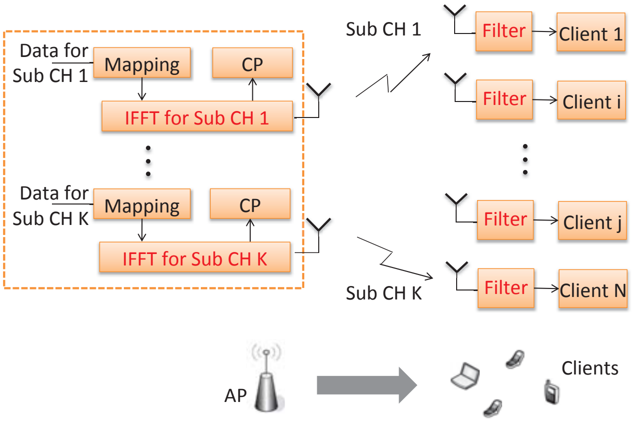

Fig. 3: Downlink transmission procedure in FC-MAC. AP utilizes band-pass filter to separate the signals from each subchannel.

ensure the QoE, the AP dynamically allocates the channel resources to the clients through two steps: 1) subchannel allocation, and 2) MAC allocation. Here we adopt an utility-based allocation scheme to achieve fair and inefficient transmission for all the clients.

Assume there are n client within the collision domain. r_{total} denotes thee total amount of channel resource, r_i is the channel resource that allocated to client i, and $T(i)$ is the traffic type of client i. Since the channel is frequency-selective fading, even given the same amount of resource, clients with the same typle of traffic may not experience the same QoE. We use normalized SNR $\frac{Eb}{N0}_i$ to represent the channel quality of client i, where $0 \leq \frac{Eb}{N0}_i \geq 1$. Therefore, the amount of resource beneficial to client i is given by $\theta_i = r_i \cdot \frac{Eb}{N0}_i$, and the utility function of client i can be represented as $U_i(r_i) = U_{T(i)}(r_i)\frac{Eb}{N0}_i$, where $U_{T(i)}(.)$ is the utility function for traffic type $T(i)$. For a marginally fair allocation $\mathcal{R} = r_1, r_2, \cdots, r_n$, each client has equal marginally utility value $u_m(\mathcal{R})$.

Our goal is to maximize $\sum_{i=1}^{n} U_i(r_i)$, with constrains $\sum_{i=1}^{n} r_i \leq r_{total}$ and $\forall r_i \geq 0$. To achieve a fair and efficient allocation, the principle is to guarantee the QoE of CBR clients, and the VBR clients follow the best effort rule. We define r_{VBR} as the amount of residual resource to be given to CBR clients, and ΔU_i is the utility gain by allocating r_i to CBR client i. As shown in Algorithm **??**, we allocation the "best subchannel" for CBR traffic and runs reservation based MAC on it, in the meanwhile choose the "worst channel" for VBR traffic and runs contention based MAC on it. In this way we ensure that each type of MAC can be benefit from the corresponding subchannels.

IV. PERFORMANCE EVALUATION

In this section, we present the trace-driven simulation results for FC-MAC using self-defined simulator intergraded with Matlab and NS-3. The traffic traces are collected over the wireless network of our laboratory. We use a typical random topology in WLANs with one AP and a maximum number of 15 clients, as shown in Fig. 4. In the following simulation scenarios, channel bandwidth is 20Mbps. The OFDM modulation is 256-point FFT, among which every 16 subcarriers are grouped into one subchannel. The propagation model is Log-Distance-Propagation under a typical WLAN working range, e.g., 10dB-25dB. Each run of a simulation transfers 2500 packets with a packet length of 1460 bytes. Detailed parameters are listed in Table II, which follows the specification of 802.11g. We first quantify the frequency domain contention in FC-MAC. After that, we present the performance of FC-MAC compared with time domain hybrid MAC under different parameters.

Fig. 4: A typical AP-Client topology in WLANs, with a maximum number of 15 clients randomly distributed.

A. *Performance of Frequency Domain Contention*

Frequency domain contention plays an essential part in FC-MAC. Its accuracy highly influence the entire throughput. Thus in this part, we first evaluate the performance of frequency domain contention using the a single collision domain topology. It should be noted that during resolution round, the contention is centralized and supervised by the AP. Thus there will be no confusion or collision. However, during transmission round, the subchannels with contention based MAC randomly generate a number as the contention metric. It is possible that two or more clients choose the same contention number and retreat transmission in this round. If this happens frequently, none of them is able to transmit and thus leads to great performance loss. Therefore, we compute the probability that two or more clients choose the same contention number P_C to see the impact of contention number collision, in terms of different subchannel bandwidth and different number of clients.

Fig. 5 depicts the collision probability in function of the number of clients. It is shown that as the number of contention clients grows, the collision probability P_C increases accordingly. That is because more clients are prone to have more same choices. To reduced this probability, we can simply increase the bandwidth of the subchannel, say, the number of subcarrier within a subchannel n. When n = 8, the contention

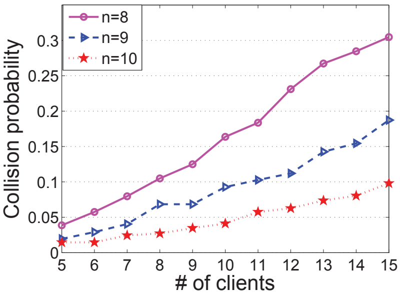

Fig. 5: Collision probability that two or more clients choose the same contention number, where n is the number of subcarrier within a subchannel.

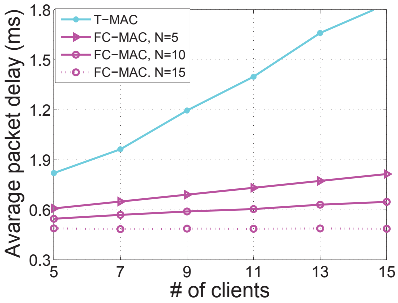

Fig. 6: The average service delay for both time domain hybrid MAC (T-MAC) and FC-MAC, where N is the total number of subchannel within a wide-band.

TABLE II: Configuration Parameters

Parameters	**Values**	**Parameters**	**Values**
SIFS	10μs	DIFS	28μs
PIFS	19μs	Symbol time	32μs
Packet length	1460bytes	Basic data rate	6Mbps

space is $2^8 - 1 = 255$, leading to a maximum collision probability of 30%. If we increase n to 10, P_C will drop quickly to only 10%. That is because the contention space increases to $2^{10}-1 = 1023$, which provides the clients a larger chance to choose different contention number from each other, and thus leads to much less performance degradation.

B. Performance of FC-MAC

In this subsection, we quantify the performance of FC-MAC compared with the time domain hybrid MAC (T-MAC), which runs different kinds of MAC protocol one after another. To ensure fairness, T-MAC also utilizes frequency domain contention and resolution as in FC-MAC. To be specific, the clients declare their transmission requests through F-RTS, and the AP specifies the transmission opportunities for each type of the MAC protocols through F-CTS. We use the parameters in Tab. II for T-MAC and FC-MAC. Two types of MAC protocols are selected for hybrid, reservation based MAC and frequency domain contention based MAC, just as the illustration in Fig. 2. To evaluate the performance of FC-MAC, we use two metrics: average service delay and aggregate throughput. The average service delay is the time that a client waits until it is able to transmit, and the aggregate throughput is calculated as the total number of non-duplicate data packets successfully received by all the designated receivers per second.

Service time: Fig. 6 describes the average service delay of T-MAC and FC-MAC in terms of number of clients. For T-MAC, it is noted that as the number of clients increase, the service time quickly grows. This is due to the fact that T-MAC hybrids the MAC protocols in time domain. Each time only one type of transmission is allowed. Thus when the number of clients increases, it cannot meet the requirements for all the clients, resulting an average service time of more than 2ms. On the contrary, FC-MAC conducts hybrid MAC in frequency domain. Since multiple MAC protocols run concurrently on each subchannel, it is capable of catering to heterogeneous needs from different clients. Therefore, as the number of clients increases, the service time does not exhibits a commensurate growth. FC-MAC also benefits from the increased number of subchannels. When the number of subchannel increases, e.g., from 5 to 15, the service time quickly drops below 0.5ms, even with the maximum number of clients. This verifies the effectiveness of FC-MAC.

Aggregate throughput: Next we compute the aggregate throughput of T-MAC and FC-MAC. The throughput is the MAC layer received data rate, which is calculated by multiplying the bits per symbol with channel bandwidth, and subtracting MAC layer overheads. Fig. 8 depicts the aggregate throughput of T-MAC and FC-MAC under 3 sets of network size from sparse to medium. Not surprisingly, the aggregate throughput of T-MAC degrades as the networks becomes crowded, and it can barely achieve a throughput that exceeds 2Mbps. Conversely, even the channel bandwidth is more narrow in FC-MAC, it can achieve an average throughout of about 3Mbps in medium network, and even 3.5Mbps in sparse network. That is because FC-MAC is capable of leveraging frequency diversity and concurrent MAC protocols to achieve the maximum multiplexing gain. Also, the transmission requests with high priority can be conducted using reservation based protocol, which ensures the aggregate throughput for most of the clients.

Variable Bit-Rates 802.11 standards provide a number of bit-rates from 6 Mpbs to 1Gbp. Therefore, it is important to know whether FC-MAC achieves high performance gain and benifit from the high speed transmission. We repeat the simulations under 3 different bit-rates, and depict the simulation results in Fig. 7. As the bit-rates increases, FC-MAC demonstrate an increasing throughput gain over T-MAC. The reason stems from the fact that FC-MAC can achieve more flexible allocation for frequency domain hybrid MAC with high speed transmission, and thus has a higher performance gain over T-MAC.

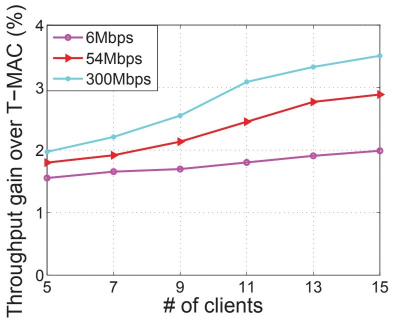

Fig. 7: Throughput gain of FC-MAC over time domain hybrid MAC (T-MAC) under variable bit rates.

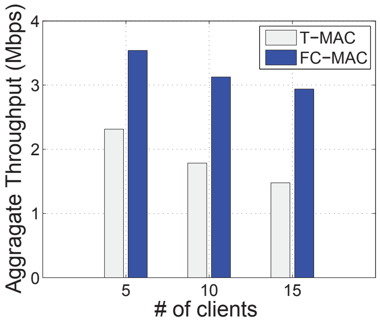

Fig. 8: Aggregate throughput of time domain hybrid MAC (T-MAC) and FC-MAC

V. CONCLUSION

In this paper, we propose a novel Fine-grained Cognitive MAC (FC-MAC) for video streaming in wireless networks. Instead of dividing channel time into slots, FC-MAC splits the channel frequency into fine-grained subchannels, and hybrids different MAC protocols in frequency domain. Our observation is that, the existing hybrid MAC protocols combine different MACs in time domain. They cannot fully utilize the channel resources, since only one type of traffic can be transmitted at a time. FC-MAC overcomes the above difficulties by transmitting multiple MAC protocols concurrently within a wideband channel, and dynamically adjusting the bandwidth and the MAC protocols according to the users' needs and channel condition. In this way it ensures the QoE at low cost and achieves high multiplexing gain. Extensive simulations verify the effectiveness of FC-MAC, demonstrating that compared with time domain hybrid MAC, FC-MAC achieves 1.9X throughput gain.

In next stage, we propose to validate FC-MAC on realtime testbed, such as SDR platform [7], and integrate more functionalities into FC-MAC to benefit more applications [17] [18], .

ACKNOWLEDGMENT

This research is supported in part by HKUST Research Grants Council (RGC) 613113, grants from 973 project 2013CB329006, China NSFC under Grant 61173156, RGC under the contracts CERG 622613 and HKUST6/CRF/12R, grant from Huawei-HKUST joint lab, Program for New Century Excellent Talents in University (NCET-13-0908), Guangdong Natural Science Funds for Distinguished Young Scholar (No.S20120011468), New Star of Pearl River on Science and Technology of Guangzhou (No.2012J2200081), China NSFC Grant 61202454. Any opinions, or conclusions expressed in this paper are those of the author(s) and do not necessarily reflect the views of the sponsor of this research.

REFERENCES

[1] E. H. Ong, J. Kneckt, O. Alanen, Z. Chang, T. Huovinen, and T. Nihtila, "Ieee 802.11 ac: Enhancements for very high throughput wlans," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*. IEEE, 2011, pp. 849–853.

[2] S.-H. Shen and A. Akella, "An information-aware qoe-centric mobile video cache," in *ACM MobiCom*, 2013.

[3] J. Chen, R. Mahindra, M. A. A. Khojastepour, S. Rangarajan, and M. Chiang, "A scheduling framework for adaptive video delivery over cellular networks," in *ACM MobiCom*, 2013.

[4] A. Farago, A. D. Myers, V. R. Syrotiuk, and G. V. Zaruba, "Meta-mac protocols: Automatic combination of mac protocols to optimize performance for unknown conditions," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 9, pp. 1670–1681, 2000.

[5] I. Rhee, A. Warrier, M. Aia, J. Min, and M. L. Sichitiu, "Z-mac: a hybrid mac for wireless sensor networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 16, no. 3, pp. 511–524, 2008.

[6] R. Zhang, R. Ruby, J. Pan, L. Cai, and X. Shen, "A hybrid reservation/contention-based mac for video streaming over wireless networks," *Selected Areas in Communications, IEEE Journal on*, vol. 28, no. 3, pp. 389–398, 2010.

[7] K. Tan, J. Fang, Y. Zhang, S. Chen, L. Shi, J. Zhang, and Y. Zhang, "Fine-grained channel access in wireless lan," in *ACM SIGCOMM Computer Communication Review*, vol. 40, no. 4, 2010, pp. 147–158.

[8] A. Bhartia, Y. Chen, S. Rallapalli, and L. Qiu, "Harnessing frequency diversity in wi-fi networks," in *ACM MobiCom*, 2011.

[9] A. Ephremides and O. A. Mowafi, "Analysis of a hybrid access scheme for buffered users-probabilistic time division," *Software Engineering, IEEE Transactions on*, no. 1, pp. 52–61, 1982.

[10] W. Ye, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *Networking, IEEE/ACM Transactions on*, vol. 12, no. 3, pp. 493–506, 2004.

[11] T. Van Dam and K. Langendoen, "An adaptive energy-efficient mac protocol for wireless sensor networks," in *Proceedings of the 1st international conference on Embedded networked sensor systems*. ACM, 2003, pp. 171–180.

[12] J. Xiao, K. Wu, Y. Yi, L. Wang, and L. M. Ni, "Pilot: Passive device-free indoor localization using channel state information," in *IEEE ICDCS*, 2013.

[13] J. Xiao, K. Wu, Y. Yi, and L. M. Ni, "Fimd: Fine-grained device-free motion detection," in *IEEE ICPADS*, 2012.

[14] C. Wong, R. Cheng, K. Lataief, and R. Murch, "Multiuser ofdm with adaptive subcarrier, bit, and power allocation," *Selected Areas in Communications, IEEE Journal on*, vol. 17, no. 10, 1999.

[15] M. Dong, L. Tong, and B. M. Sadler, "Effect of mac design on source estimation in dense sensor networks," in *Acoustics, Speech, and Signal Processing, 2004. Proceedings.(ICASSP'04). IEEE International Conference on*, vol. 3. IEEE, 2004, pp. iii–853.

[16] L. Wang, K. Wu, and M. Hamdi, "Combating hidden and exposed terminal problems in wireless networks," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 11, pp. 4204–4213, 2012.

[17] Y. Zhu, Z. Li, H. Zhu, M. Li, and Q. Zhang, "A compressive sensing approach to urban traffic estimation with probe vehicles," *Mobile Computing, IEEE Transactions on*, vol. 12, no. 11, pp. 2289–2302, 2013.

[18] Y. Zheng and M. Li, "Pet: Probabilistic estimating tree for large-scale rfid estimation," *Mobile Computing, IEEE Transactions on*, vol. 11, no. 11, pp. 1763–1774, 2012.