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Advances in IEEE 802.11ah Standardization for Machine-Type Communications in Sub-1GHz WLAN

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***Abstract*—The IEEE 802.11ah task group has been formed to develop the specification for sub-1GHz WLAN. Due to the low operating frequency, it is expected that the 802.11ah can support coverage up to 1km. Such large coverage is well-suited for machine-to-machine (M2M) or machine-type communication (MTC) applications like smart grid and sensor networks. These applications are characterized by large number of operating devices, small data packet size, and low-power operation, and they pose new problems that conventional 802.11 WLAN is not capable to address. Therefore they stimulate significant interest and discussion in the task group to define enhancements to improve the performance of 802.11ah WLAN. The objective of this paper is to present the recent advances in the IEEE 802.11ah standardization to enhance the MTC performance. In particular the emphasis is on the channel access enhancement, which lies in the core of MAC layer. Relevant works in the research community are also reviewed in the hope that they may be utilized to further optimize the 802.11ah WLAN.**

Keywords*—IEEE 802.11ah, extended-range Wi-Fi, M2M, MTC, sensor network, smart grid, sub-1GHz, WLAN.

I. INTRODUCTION

Recently, the IEEE 802.11 Task Group ah (TGah) is formed to work on specification for sub-1GHz WLAN. The scope of the amendment defines an OFDM Physical layer (PHY) operating in license-exempt bands below 1 GHz, and enhancements to the IEEE 802.11 Medium Access Control (MAC) to support the PHY. Some examples of the sub 1GHz license-exempt bands include 868-868.6 MHz in Europe, 950-958 MHz in Japan, and 902-928 MHz in US. Thanks to the low operating frequency, the IEEE 802.11ah standard aims to provide support for transmission range up to 1 km, as well as data rates greater than 100 kbps [1]. Due to the large coverage, the potential use cases for IEEE 802.11ah standard fall into three general categories including sensor/meter network, backhaul for sensor and meter data, and extended range Wi-Fi for cellular data offloading [2][3]. More usage examples are given in the 802.11ah use case document [2].

One of the major use cases for the IEEE 802.11ah standard is support for machine-to-machine (M2M) or general machine-type communications (MTC) such as smart grid and sensor networks. In fact, the growing interest in MTC has already driven various standardization groups to define specifications in both licensed and license-exempt frequency bands. For example, the 3GPP has started studies on enhancement to support efficient network access for MTC [4] and reduce cost of MTC devices [5]. The IEEE 802.15.4g task group has created the amendment to support smart utility network [6]. The IEEE has also formed 802.16 M2M TG and created P802.16p and P802.16.1b amendments. The IEEE 802.11ah complements the other standards to provide support for MTC in local area network using a different spectrum from the highly congested WLAN operating at 2.4GHz/5GHz ISM bands. The IEEE 802.11ah standard also aims to support cellular data offloading, but the main focus of this paper is on the use case relevant to MTC, as such use cases pose several interesting challenges that require significant enhancement to the current IEEE 802.11 standard.

As the TGah specification development process is still on-going, this paper does not aim to provide a full detailed description of the standard, but rather to highlight some important design concept and rationale, as well as review relevant research works that may be utilized to enhance the performance of IEEE 802.11ah. The rest of the paper is organized as follows. The MTC traffic is first characterized in Section II. PHY and MAC enhancements to address MTC challenges in 802.11ah are then described in Section III. In particular, the channel access enhancement, which is considered as the core of MAC design, is discussed and evaluated in Section IV and Section V, respectively. The paper is concluded in Section VI.

II. MTC TRAFFIC FEATURES AND CHALLENGES

MTC applications are characterized by a large number of low-power devices transmitting small amount of data, which poses several challenges to the design of wireless networks. This section provides an overview of MTC features and design challenges.

Firstly, a large number of devices (STAs) must be supported. For example, one typical 802.11ah use case, smart grid meter to pole [2], requires one access point (AP) to support up to 6000 outdoor STAs. Even for other applications like environment or agriculture monitoring, one AP needs to support up to 300 STAs. Although the target 802.11ah STA/AP capacity far exceeds the current capacity of 802.11 basic service set (BSS), under normal operation it is expected that the traffic is infrequent with period ranging from tens of seconds to a few hours [5][7], and will not create much burden on the

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network. However, when the traffic generation is triggered by events like power outage, these STAs will attempt to access the channel and transmit data almost simultaneously. The performance drop caused by the simultaneous authentication and association of a large number of STAs after power outage has been evaluated in TGah [8]. The simulation result shows that the time taken for all STAs to authenticate and associate successfully with the AP increases significantly with the number of contending STAs as a result of severe collision. It is the simultaneous attempts to use the channel that will result in collision and retransmission and will overload the network [4]. Therefore new channel access schemes are needed to solve this issue.

Another feature of MTC traffic is that the data packet size is small, typically less than 200 bytes [5]. For such small data transmission, overhead becomes significant. The overhead may be caused by the PHY / MAC headers, the communication protocol, and the channel access mechanism [9].

Finally, low-power operation is desirable for sensor/meter network. There are several sources of energy wastage in a wireless network [10]. When a transmitted packet is not acknowledged properly, it needs to be retransmitted at the cost of additional energy. A STA also needs to spend time and energy to listen to the wireless medium to synchronize to the network, to detect if the channel is available, and to perform necessary backoff before using the channel. Thus, energy wastage is significant in a congested network dominated by collisions and backoffs.

III. ENHANCEMENT FOR MTC

As discussed previously, MTC is typically characterized by the transmission of a small amount of data by a large number of low-power STAs over a large coverage area. To enhance the MTC performance, many PHY and MAC proposals have been submitted and discussed in TGah. In this section, some of the PHY and MAC features that have been adopted in the IEEE 802.11ah specification framework document (SFD) [11] are described.

A. *Coverage Extension*

One of the most important design objectives for PHY is to support large coverage. In general, PHY follows largely from IEEE 802.11ac design with a 'down-clocking by 10' approach. To further provide 3dB gain, a new MCS0-Rep2 mode is introduced to enhance coverage. The transmission flow for MCS0-Rep2 mode is shown in Fig. 1. Only a single space-time stream is used in MCS0-Rep2 mode, and the repeat-by-2 block is performed on a per-OFDM symbol basis.

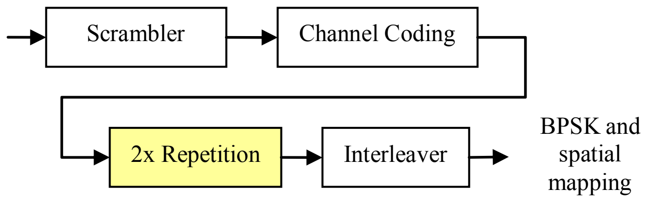

Fig. 1. Transmission flow for MCS0-Rep2 mode

B. *Support for Large Number of STAs*

Based on the current 802.11 specification, a STA operates in either active mode or doze mode. When a STA indicates to AP that it is in doze mode, AP will buffer any downlink traffic to the STA and inform the STA availability of downlink buffered data via the Traffic Indication Message (TIM) information element (IE) in Beacon. The TIM is basically a bitmap that uniquely maps to the Association Identifier (AID) of the STAs. A bit is set when the corresponding STA has buffered data at AP, and the corresponding STA then transmits the power-saving poll (PS-Poll) frame to AP to poll the buffered data. As the maximum size of an IE is 256 bytes, a maximum of 2007 AIDs can be supported (after subtracting fields used for other signaling purposes). In other words, each TIM IE can address up to 2007 STAs. However, as described in the 802.11ah use case document [2], up to 6000 STAs need to be supported. Moreover, using a bitmap to support 6000 STAs may increase the beacon size significantly, and it is desirable to reduce the size of TIM [12]. Hence, efficient addressing/encoding method is needed in 802.11ah.

The concept of hierarchical TIM bitmap and TIM segmentation has therefore been proposed and adopted in the 802.11ah SFD [11]. The hierarchy of TIM comprises 4 pages, each containing 32 blocks. Each block is further divided into 8 sub-blocks of 8 bits each. A STA is identified by its page index, block index within the page, sub-block index within the block, and its bit position within the sub-block, and the address of the STA is encoded in its AID. The hierarchical TIM bitmap and AID structure are shown in Fig. 2 [11].

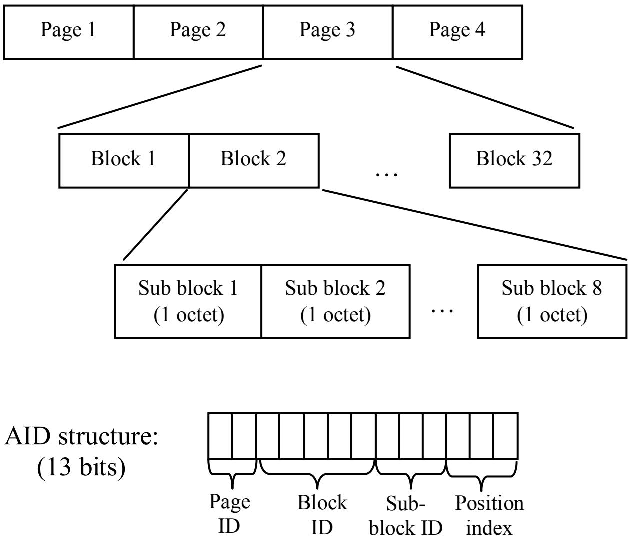

Fig. 2. Hierarchical TIM and AID structure

As the number of STAs that can be addressed within a beacon interval is limited, the TIM bit map is divided into segments. Each segment may contain several blocks from the same page that is transmitted in one beacon. Furthermore, the new TIM format also signals the bitmap for sub-blocks. If none of the 8 STAs within a sub-block have buffered data at AP, the corresponding bit in block bitmap is not set, and the 8 zero-bits are not transmitted. In this way, the original bitmap can be compressed by removing the consecutive AIDs that do not have buffered data at AP.

It is desirable to reduce the beacon size by compressing the TIM. As the encoding efficiency depends on the distribution of set bits in the original TIM bitmap, TGah adopts several other methods to efficiently encode the bitmap, and the encoding method for each block is defined in the block control field. Thus the encoding for different blocks may not be identical. For example, when there are only buffered data for a single STA, it is more efficient to explicitly indicate the AID of the STA instead of transmitting a bitmap, and TGah defines the 'single AID mode' of encoding. The single AID mode can be further optimized with differential encoding to support multiple AIDs. On the other hand, when there are only a few bits that are not set in the original bitmap, it is more efficient to encode these zero bits, and an 'inverse bitmap mode' is defined that first inverts the original bitmap before encoding.

Besides new methods to address up to 6000 STAs, the distributed channel access mechanism defined in current 802.11 standard needs to be enhanced too, and a dedicated discussion on channel access enhancement is discussed in Section IV.

C. *Support for Small Data Transmission*

As discussed in Section II, overhead becomes significant for MTC when the transmitted data packet size is small, and sources of overhead include frame header and communication protocol. To reduce the overhead in MAC header, short MAC header has been defined in 802.11ah. The size of MAC header for typical 802.11 data frame is 28 bytes, which is reduced to 18 bytes in 802.11ah short MAC header. TGah also introduced several null data packet (NDP) frames, also known as short frames, such as short ACK, short block ACK, short CTS, and short PS-Poll. These short frames do not carry MAC protocol data unit (MPDU) and they are only differentiated in their SIG field, which contains 36 bits for 1MHz bandwidth and 48 bits for 2MHz and greater. The SIG field now carries the signaling information that is used to be conveyed in the MPDU. As the MAC information bits are shifted into PHY, efficient design is needed without compromising the performance. These short frames reduce the protocol overhead as well.

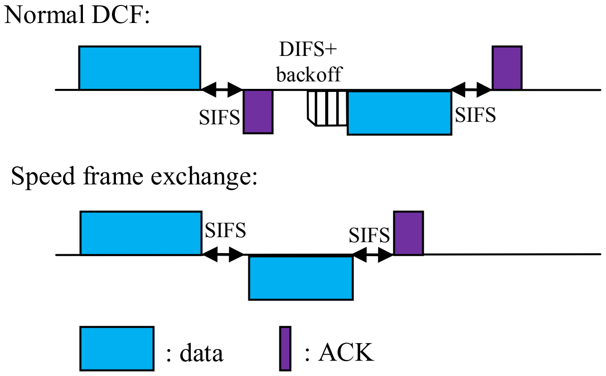

Fig. 3. Speed frame exchange

Overhead may also arise from the communication protocol. To reduce the overhead in communication protocol, TGah has also introduced new frame exchange protocols with reduced protocol overhead. One such example is speed frame exchange that uses data frame as ACK shown in Fig. 3. Compared to normal DCF, speed frame exchange uses the data frame as the ACK to previous data frame. As the frame spacing used in speed frame exchange is the short interframe space (SIFS), speed frame exchange also reduces the channel contention time due to the DCF interframe space (DIFS) and random backoff.

D. *Support for Low-Power Operation*

Current 802.11 standard requires that a power-saving STA in BSS to listen to AP's beacon upon waking up. In the actual deployment, both AP and STA suffer from clock drift, and the STA has to wake up early enough to compensate for the worst-case clock drift in order not to miss the beacon. Energy is wasted in the idle listening period before beacon arrival. To reduce energy wasted in receiving the beacon, AP may indicate its clock accuracy so that STAs do not need to assume the worst-case scenario. In the case that AP has a stable clock, STAs can afford to stay in doze mode longer.

To further reduce the energy consumed to receive beacon, some low-power STAs do not even need to listen to the beacon. These STAs are known as non-TIM STAs in that they may send PS-Poll/trigger frames any time to AP to check availability of buffered downlink data and hence they do not necessarily need to have a TIM entry in beacon.

Energy is also wasted when the STA retransmits a packet after collision. To reduce collision probability, new channel access schemes have been proposed to spread the uplink traffic, as discussed in the sequel.

IV. CHANNEL ACCESS

Channel access mechanism lies in the core of MAC design. Current channel access is mainly based on distributed coordination function (DCF) and optional point coordination function (PCF) [13]. In 802.11e, enhanced versions are also specified, namely enhanced distributed channel access (EDCA) and optional HCF (hybrid coordination function) controlled channel access (HCCA), but the fundamental principle remains the same. In DCF and EDCA, channel access is contention-based, whereas in PCF and HCCA, channel access is controlled by AP. DCF works well when the contention domain is small, and this is the case when the number of STAs in a BSS is small (e.g. less than 50 STAs per AP), or the data transmission is relatively infrequent. However, when the network is overloaded with many STAs attempting to access the channel simultaneously, a large contention domain is created and the contention-based distributed channel access mechanism becomes inefficient.

A. *Access Control*

Access control is a common technique used to resolve the large contention domain. In 3GPP, access barring is specified for MTC to prevent network overloading [4]. One similar technique is used in IEEE 802.11ah to address the issue of association and authentication of a large number of STAs, where the AP limits the number of STAs to be authenticated /associated at the same time by broadcasting a value V in the beacon. Each STA also generates a random number R locally and compares R with V. The STA can only transmit authentication request if $R \leq V$. Otherwise it has to defer its transmission [8]. By limiting the number of contending STAs, the STAs' traffic is spread over prolonged time duration. However, the number of collisions is reduced and the channel can be used more efficiently. Hence the total channel time used can be shorter than the case without access control.

To use the channel efficiently, AP needs to sense the number of contending STAs to properly design the control value V, and this has been studied extensively. One of the pioneering works in the modeling and analysis of IEEE 802.11 DCF is [14], where a Markov Chain model is built based on the STA's backoff state. The model has been further refined in [15] to describe the protocol more accurately by imposing the retransmission limit and backoff counter freezing and to cater for both saturated and unsaturated traffic cases. Based on the analytical result, by observing the parameters such as number of failed and successful transmissions in the channel, AP is able to estimate the number of contending STAs. The estimation can be made more accurate by incorporating other parameters such as slot utilization rate [16]. Further enhancement is still needed to find the optimum V in real time. As suggested in [8], AP may utilize additional information such as its buffered management frames that reflects the network congestion level to refine V.

B. *Slotted Access*

In IEEE 802.11ah, AP may also have more control on the channel by defining the restricted access window (RAW), where the channel is divided into multiple slots and each slot may be used by one or multiple STAs [11]. This is effectively a more scheduled way of spreading the traffic to reduce the collision probability in each slot. The RAW definition is carried in the newly introduced RAW parameter set (RAW-PS) IE in beacon. The usage of RAW can be flexible to address different channel access scenarios.

When the contention domain is small, the RAW can be used as a high level spreading prior to DCF as shown in Fig. 4, where the STA is allowed to poll the AP for downlink data at its designated slot. Several STAs may possibly be assigned to the same slot. The major drawback of this scheme is that it may yield empty slot (e.g. for STA 2 and STA 4), as AP is not aware whether the STAs are in active mode or doze mode. Instead of implicit slot assignment in beacon, AP may also schedule the STAs' channel usage by transmitting a resource allocation (RA) frame at the start of RAW. The RA frame indicates explicitly the slot assignment for each STA.

In the aforementioned schemes, AP may predict the degree of contention based on its buffer status and designs the RAW parameters accordingly. One issue with this approach is the RAW slots are not used efficiently, and some slots may be unused while some may be congested. An alternative approach to improve channel access efficiency is that STA may first transmit short frames to indicate to AP that it is awake and possibly also to indicate it has uplink data. The short frames may be transmitted based on contention, or AP may dedicate another RAW for contention-free transmission of short frames as shown in Fig. 5. The first RAW is designed for short frames from all STAs with smaller RAW slot duration. Although there may be empty slots, the channel time is not wasted much. Based on the polling result in RAW 1, AP is more informed of the STA's status and can schedule the data transmission more efficiently via RA frame to eliminate empty slots in RAW 2.

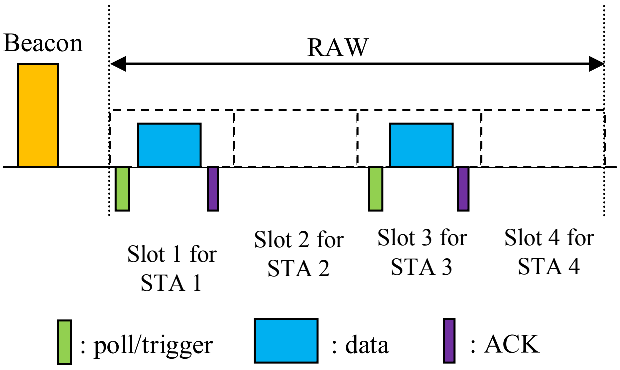

Fig. 4. RAW based channel access

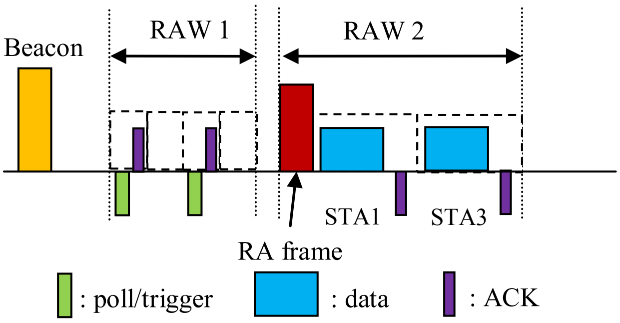

Fig. 5. Dedicated RAW for short frames

V. SIMULATION OF CHANNEL ACCESS

The MTC channel access performance is characterizd and evaluated via Matlab simulation of a single BSS without other overlapping BSS. To concentrate on the MAC layer channel access performance, the simulator does not assume any PHY impairment. We assume that the STAs are static, and can hear each other. Therefore no RTS/CTS is used. The clear channel assessment (CCA) time and the slot time are both 50 us. SIFS is 150 us. The transmitted packet duration is 1ms. A packet is dropped after a retry limit of 20. The minimum and maximum contention window sizes are 31 and 1023 respectively.

Fig. 6 shows the average number of collisions when the STAs attempt to transmit packets. The total number of collisions in the BSS are normalized by the total number of STAs to yield the average value. The random triggering of channel access follows uniform distribution within different intervals from 1ms to 10 sec. The traffic arrival interval is controlled by application, and effectively determines how the STA traffic is spread out. Under normal operation where STAs periodically send data to the AP, the trafic arrival interval can be a few minutes or even hours. It can be seen from the simulation result that a STA almost encounters no collision when the traffic is spread across 10 sec even for a BSS comprising 2000 STAs. On the other hand, when the traffic arrival interval is small, several STAs may attempt to access the channel simultaneously, which gives rise to collisions.

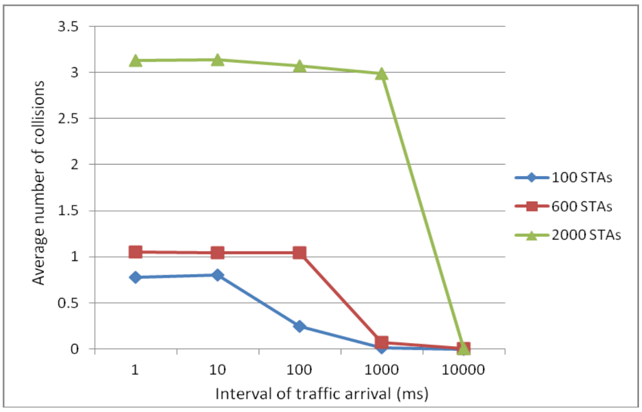

Fig. 6. Effect of traffic arrival interval

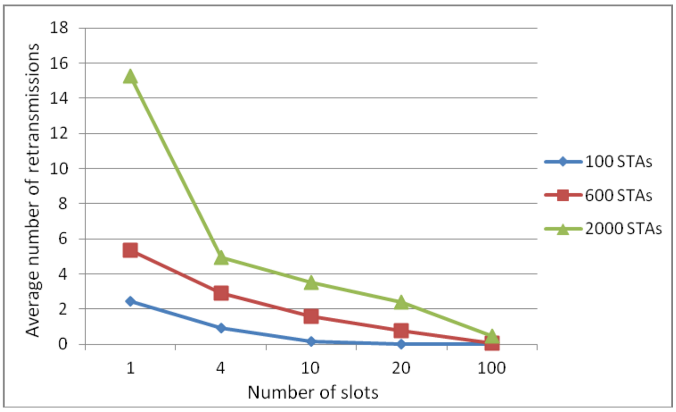

Fig. 7. Effect of number of slots

It can be seen from previous result that the number of collisions is reduced when the traffic becomes more spread. However, sometimes the application may trigger a large number of STAs to transmit packet simultaneously. Therefore traffic spreading has to be done at the MAC layer using the schemes discussed in Section IV. Due to space limitation, we will only use the general framework of slotted channel access where a STA is assigned to a RAW slot. The total number of slots and the assignment of STAs to slots are broadcasted by the AP. The STA then uses normal DCF within the slot to access the channel. The slotted channel access becomes the current DCF when there is only a single slot. The average number of retransmissions against the number of slots is shown in Fig. 7. The traffic arrival interval is 6 ms. As expected, using more slots to spread the traffic reduces the retransmission, which is beneficial for low-power operation.

VI. CONCLUSION

The IEEE 802.11ah standard has drawn strong interest and numerous contributions with significant number of new features specified in the SFD draft. It is expected that the internal task group ballot will be in March 2013, and initial letter ballot to be in July 2013. This paper highlights some design concept and rationale in IEEE 802.11ah standard with the objective to enhance MTC performance in sub-1GHz WLAN such as coverage extension, support for a large number of devices, overhead reduction, and low power operation. Particular emphasis is put on channel access mechanisms that leverage on traffic spreading. The IEEE 802.11ah standard can flexibly support several channel access schemes to cater for different MTC application scenarios. It also opens new research topics to further optimize the MTC WLAN performance.

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