Sector-based RTS/CTS Access Scheme for High Density WLAN Sensor Networks

Stefan Aust
NEC Communication Systems, Ltd.,
1753 Shimonumabe, Nakahara-ku,
Kawasaki, Kanagawa 211-8666, Japan
stefanaust@ieee.org

R. Venkatesha Prasad,
Igns G.M.M. Niemegeers
EEMCS, Delft University of Technology,
P.O. Box 5031, 2600 GA Delft, The Netherlands
rvprasad@ieee.org; I.G.M.M.Niemegeers@tudelft.nl

Abstract—Wireless LANs (WLANs) are increasingly becoming popular. Indeed the trend is to use WLAN interfaces in many instruments and devices. This increasing number of user terminals in WLANs has thrown new access issues. This motivates the redesign of the current wireless media access schemes. We analyze the performance of such high density WLANs and discuss the limitations of the IEEE 802.11 Distributed Coordination Function (DCF) when request to send/clear to send (RTS/CTS) is used as a media access management scheme. Our numerical evaluation and simulation studies exhibit a significant performance reduction when the RTS/CTS access scheme is used due to an increased number of RTS frame collisions. This happens when the density of WLANs starts increasing. We thus propose a novel sector-based RTS/CTS scheme that allows a significant throughput improvement for massive access scenarios in high density WLANs by utilizing a spatially orthogonal access scheme. This type of access scheme would be particularly beneficial in machine-to-machine (M2M) communication networks and for internet of things (IoT) applications.

Index Terms—WLAN, IEEE 802.11ah, sub-1 GHz, high density, massive access, beam forming, spatial orthogonal.

I. INTRODUCTION

The high density of multiple wireless terminals in a single wireless LAN (WLAN) coverage area throws many challenges for the current IEEE 802.11 WLAN design [1]. An important challenge is scalability. A simple one-hop deployment, e.g., one access point (AP) and hundreds of WLAN stations (STAs), results in a high density of a WLAN. The installation of outdoor WLANs, e.g., based on the upcoming IEEE 802.11ah standard [2], will enable new use-cases and scenarios, such as smart grid, machine-to-machine (M2M) and internet of things (IoT) applications [3]. Such deployment scenarios are quite similar to those problems and scenarios discussed in cellular systems [4], [5]. In addition, high dense deployment is also in the focus of radio frequency identifier (RFID) network designers [6]. An increased number of associated WLAN STAs leads to well-known loss of saturated throughput performance [7].

In this paper, we explore the problem of massive access in large density WLANs and propose an enhanced request to send (RTS) and clear to send (CTS) management scheme [1]. Our contributions are:

1) We identify the limitations of IEEE 802.11 media access control (MAC) in high density WLANs;

2) We analyze the boundaries of IEEE 802.11 MAC RTS/CTS and the impact of RTS frame collisions;

3) We introduce enhancements to RTS/CTS to reduce the RTS management frame collisions.

This paper is organized as follows. We discuss the IEEE 802.11 MAC challenges for high density WLANs in Section II. Section III outlines an overview about the upcoming IEEE 802.11ah WLAN protocol amendment. Our proposed RTS/CTS enhancement is presented in Section IV, followed by a detailed performance evaluation in Section V. We proceed with discussing the effect of our proposal in Section VI and summarize our findings in Section VII.

II. PROBLEM DESCRIPTION

Let us define a user as an individual or group of wireless stations \( s_i \). We motivate the problem of massive access due to the theoretical number of WLAN stations \( \rho_\gamma = \sum s_i \) within coverage radius \( r_\gamma \) of AP\( \gamma \). Next, without loss of generality, let us assume a uniform density \( \theta \) per \( km^2 \) of WLAN users. For WLANs as mentioned in [2], with \( r_\gamma = 1000 m \) and \( \theta = 2000 \) – a density, which is practical to assume for metropolitan cities, such as Tokyo or Sydney – the number of STAs within AP coverage \( \gamma \) would increase to a maximum number \( \rho_\gamma = 6283 \) STAs using the basic density function \( \pi(r/1000)^2 \theta \) [8]. This higher density of STAs leads us to the issue of supporting their access to the medium in WLANs. Other massive access scenarios are discussed for M2M communication in cellular systems in [9].

In addition, if the AP coverage range \( r_\gamma \) increases, e.g., \( r_\gamma > 1 \ km \), such as for the suggested ultra-high frequency (UHF) WLANs operating in the sub-1 GHz ISM frequency bands – the number of \( n_{\gamma} \) STAs that are in AP coverage can be significantly higher than the upper boundary of supported WLAN STAs, which is 2007 [1].

As an enhancement of the carrier sense multiple access/collision avoidance (CSMA/CA) media access scheme in WLANs, the RTS/CTS access scheme is a favored method selected by WLAN operators to reduce data packet collisions [10]. It will help in reducing the probability of data packet collisions caused by the presence of hidden terminals. When RTS/CTS is applied, a sender broadcasts RTS frames to announce that a data packet is ready to be sent. Then, the
data packet will be sent after receiving the CTS notification from the receiver. Surrounding users will notice the RTS/CTS handshake procedure and will refrain from any data transmission to reduce the probability of data collisions during the transmission. In the case of large density WLANs, it is not well understood how RTS/CTS may contribute on the collision probability, e.g., due to the potential collisions of RTS frames. The problem is, if the number of users increases, the effect of an increased RTS frame collision may be severe, which may lead to throughput reduction in large density WLANs. In this study we will apply a novel RTS/CTS model for large density networks. We will demonstrate that the network density of users has an impact on the RTS frame collision probability. As a remedy, a sector-based RTS/CTS access scheme is proposed in this paper. We demonstrate a significant reduction in RTS frame collisions when our proposed scheme is applied in large density WLANs.

III. LONG-RANGE WLAN: IEEE 802.11ah

The upcoming IEEE 802.11 amendment proposes avenues for two new directions in licensed-exempt WLANs. First, IEEE 802.11ah will be applicable in wireless sensor networks (WSNs), as a so-called WLAN sensor. It is envisioned that such WLAN sensors will be much faster to deploy compared to IEEE 802.15 and simple to use, similar to Wi-Fi at home or office. Second, IEEE 802.11ah will be highly suitable for long-range outdoor resilient wireless communications. New use cases are envisioned, such as long-range sensor networks, emergency networks, and smart grids. The IEEE 802.11 WLAN protocol family will be an important technology for outdoor wireless communication in the near future.

IEEE 802.11ah is a new sub-1 GHz radio-band Wi-Fi, which is currently under standardization, adding the 920 MHz band to the family of IEEE 802.11 WLAN protocols. Improved wireless coverage range (indoor and outdoor), low power consumption (supporting 5 to 10 years battery lifetime), and rich data rates (low data rates for sensor applications at 150kbps, mid/high data rates up to 78Mbps in countries with high tx power limit and wide bandwidth) will be the primary reasons to select IEEE 802.11ah WLANs. Most importantly, IEEE 802.11ah WLAN offers a wide range of new wireless technology, compared to the outdated IEEE 802.15.4 protocols. It supports multi-antenna multiple-input multiple-output (MIMO) orthogonal frequency division multiplexing (OFDM), high throughput (HT) protocol preambles, based on IEEE 802.11ac, outdoor channel models, precoding schemes for spatial multiplexing, and multi-user MIMO (MU-MIMO).

Most of the proposed IEEE 802.11ah use cases want lower power and extended coverage range and are willing to give up on throughput. Data are typically short and bursty and IEEE 802.11ah PHY, channel sounding, and MAC facilitates special features for IoT type applications.

IEEE 802.11ah is envisioned to provide IP connectivity to all types of devices that are currently not connected to the internet and have yet to be invented. A special $2 \times$ repetition mode will be introduced with the IEEE 802.11ah amendment allowing ultra-robust over a large coverage range. IEEE 802.11ah inherits the baseline design of IEEE 802.11ac and IEEE 802.11n and is optimized for robust link and extended coverage in the sub-1 GHz radio-band. Spectral selective transmission (SST), restricted access window (RAW) and target wake-up time (TWT) are new MAC enhancements, introduced to the IEEE 802.11ah protocol. In addition, IEEE 802.11ah is a well optimized WLAN protocol for sensor applications. Scalability support allows to link thousands of nodes by a single WLAN AP in a one-hop fashion.

IV. PROPOSED SOLUTION

A. Model Description

We propose an enhanced MAC RTS/CTS scheme based on a WLAN group assignment to schedule RTS frame transmissions. A group can be defined in different ways, a logical group defined by the address identifier (AID), a physical group defined through receiving beacons from the WLAN AP, and a combination of both. We argue that the physical group has advantages, such as utilizing a simple sectorized beam forming where beacons are broadcast to a specific location, which we called spatial orthogonal access. The sector-based RTS frame transmission utilizes distinct wireless areas by dividing the AP WLAN coverage area into sectors.

Fig. 1 shows a sectorized coverage area of a single $AP_j$ with station $s_{j,i}$ in sector $j$. The sectorization divides the AP coverage into sectors $\Psi_j$ in that RTS frames from stations located in orthogonal sectors – here, $s_{j,i}$, $s_{j+1,i}$, $s_{j+2,i}$, $s_{j+3,i}$ do not interfere with each other. The transmission of RTS frames in orthogonal sectors is scheduled at $t_{j,i}$, $t_{j+1,i}$, $t_{j+2,i}$ in $\Psi_j$, $\Psi_{j+1}$, $\Psi_{j+2}$, respectively by frequently broadcasting time management frames [1] with tokens as defined in IEEE 802.11-2012 from the AP to the stations. The described orthogonal sectorization avoids the concurrent emission of RTS frames amongst adjacent AP sectors. Note that in addition to reducing the mutual interference amongst stations, the proposed orthogonal sectorization has the potential to reduce the mutual interference amongst adjacent $AP_j$, $AP_{j+1}$, $AP_{j+2}$,..., so forth, when a distributed network sectorization scheme is applied.

In Fig. 1 the beam of $AP_j$ encompasses a sector $\Psi_{j,i}$ with a group of STAs $s_{j,i}$. Given the number of terminals $s_{j,i}$ in sector $\Psi_{j,i}$ we have,

$$\sum_{\forall k \in \Psi_{j,i}} s_{j,i} \ll \sum_{\forall k \in AP_j} s_{j,k}$$

(1)

as the set of terminals $s_{j,i}$ in sector $\Psi_j$. During a single time frame $T_{frame}$ the CSMA/CA media access is given amongst $s_{j,i}$ terminals in $\Psi_j$ with,

$$\Delta(j, T_{frame}) = s_{j,i} \cdot T_{frame}.$$  

(2)

We then use a simple model, which accounts for all exponential backoff protocols, details are reported in [7]. We use this model to estimate the saturated (asymptotic) throughput, which
is essential for the performance evaluation of our proposed WLAN AP sectorization.

Since $n$ stations contend for the channel, and each transmits with a probability $\tau$, the probability of one transmission per slot time $P_{tr}$ is given by,

$$P_{tr} = 1 - (1 - \tau)^n.$$  \hspace{1cm} (3)

The probability for a successful transmission, $P_s$, on the channel is given by

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n},$$  \hspace{1cm} (4)

with the transmission probability of a single station,

$$\tau = 1/n\sqrt{T_c/2},$$  \hspace{1cm} (5)

for the sensed busy time $T_c$ during a collision.

The normalized throughput $S$ is defined as the fraction of time the channel is used to successfully transmit data bits during any chosen slot time and is given by,

$$S = \frac{P_sP_rE[P]}{(1-P_{tr})\sigma+P_{tr}P_sT_s+P_{tr}(1-P_s)\eta},$$  \hspace{1cm} (6)

where $T_s$ is the sensed busy time of a successful transmission, $\sigma$ is the duration of an empty slot, and $\eta$ is the residual frame collision coefficient. We argue that by reducing the RTS frame collision probability a significant increase in saturation throughput can be achieved. A reduced RTS frame collision probability can be obtained through sectorization of $AP_{\gamma}$ with $\Psi_j$. We model our proposed sector-based RTS frame transmission scheme and modify (6) by altering the collision probability from (2) and get,

$$\eta = P'_{c,\Delta}T_c.$$  \hspace{1cm} (7)

The RTS frame collision probability $P'_{c}$ is derived from [10],

$$P'_{c} = \left(1 - (1 - p\eta)^{\nu(n-1)}\right),$$  \hspace{1cm} (8)

with

$$p\eta = 1 - \left(1 - \frac{1}{W_{avg}}\right)^{n-1},$$  \hspace{1cm} (9)

where $\nu$ is slot time in $\mu$s and $W_{avg}$ is the average backoff window size. Fig. 2 illustrates the backoff performance for different window size, 64, 512, and 1024 B.

B. Practical Deployment Scenario

WLAN sensors may collect ambient information and send them to the AP while the WLAN sensors contend for wireless access to the network. When multiple WLAN sensors try to access at the same slot, they contend by the random backoff procedure. To assign the WLAN sectors in practical WLAN systems, the optional IEEE 802.11n down-link beam forming of the WLAN AP is applied. All non-AP STAs within a beam sector receive the sector information combined with pre-defined IEEE 802.11n time frames. The broadcast information increase the accuracy of the medium access. An increased beam distance between adjacent sectors allows a controlled invocation of RTS frames to reduce the RTS frame collision probability, which supports a larger number of associated STAs while the interference is reduced. An optional bit sequence in the IEEE 802.11ah MAC frame is used to advertise the sectorized beam forming medium access.

V. PERFORMANCE EVALUATION

A. Scenario and Model Evaluation

Let us assume that our WLAN consists of $n$ STAs. We utilize the distributed coordination function (DCF) CSMA/CA as the mandatory MAC function including the RTS/CTS procedure. The RTS/CTS exchange is performed by each STA, which provides a fast collision interference detection and transmission path check. A STA may repeat the RTS/CTS procedure if a CTS was not being received, e.g., due to wireless link outages. A sender must wait for a channel to be idle for distributed inter-frame space (DIFS) time before it can start to transmit. If the wireless channel is sensed busy, it back off its transmission by a random length of time to avoid collisions. As a prerequisite, saturation condition is assumed in that backoff slots and transmissions continuously occur as the time evolves [11]. In the random network, WLAN sensors try to access the up-link channel based on the random backoff mechanism during a time-slot. Thus, the transmission
behavior of WLAN can be approximated by that of IEEE 802.11 stations in the saturation condition.

B. Model Validation

A simulation study was conducted to validate the model. We applied the 1.0 Mbps mode that is at the upper bound of an IEEE 802.11ah WLAN operating at 1 MHz bandwidth (2 × 2 MIMO-OFDM). Simulation parameters are given in Table I. To comply with the CTS procedure, a STA that receives an RTS frame addressed to it considers the network access vector (NAV) to determine whether or not to reply with a CTS frame. For the model validation, let us assume that a STA is ready to send and set the NAV counter to 0 indicating that the STA is idle. We then conduct the validation by identifying the saturated throughput performance over a large number of STAs.

VI. DISCUSSION OF EVALUATION RESULTS

We discuss our simulation results of saturated throughput performance for different network densities. Starting with 1 and 10 STAs the saturated throughput reaches a value of 0.8 while using CSMA/CA, which is higher than the observed RTS/CTS performance due to the overhead of the WLAN management frames (Fig. 3). If more than 10 STAs are within AP coverage, RTS/CTS significantly outperforms the CSMA/CA access scheme due to the mitigated collision probability when using RTS/CTS management frames. The observed throughput results are similar to the observations reported in [7]. In [7], it was argued that RTS/CTS clearly outperforms CSMA/CA due to reduced collision probability by performing resource allocation amongst STAs.

In addition, Fig. 3 depicts that if more than 100 STAs are within coverage, the RTS/CTS throughput performance suffers due to the impact of increased RTS frame collisions, which we observed in our simulations. We conclude that both medium access schemes, CSMA/CA and RTS/CTS, limit the network performance in high density WLANs.

Next, we discuss the throughput performance of RTS/CTS access scheme and compare them with our proposed sectorized medium access scheme, which is presented in Fig. 4.

The figure illustrates the improved performance for $n > 100$ and indicates a 5.5 times larger number of STAs within the coverage area, when we compare at 80% saturated throughput (packet length 1023 byte). By further reducing RTS frame collisions, the proposed solution achieves higher throughput over large $n$. We observe similar improvements even for short packet length (200 byte). We claim that the proposed spatial orthogonal access scheme reduces the RTS frame collisions.

Next, we identified access regimes that require different carrier sensing management schemes. We propose three regimes and define decision thresholds: (i) $\chi = \sum s_{\gamma,i}$ as the sum of STAs associated with AP $\gamma$; (ii) if $\chi \geq 100$ STAs, the proposed scheme enables the reduction of RTS frame collisions, (iii) if the number of STAs is between $\chi < 100$ and $\chi \geq 10$, RTS/CTS access scheme must be applied, whereas with $\chi < 10$ STAs CSMA/CA must be used to minimize the transmission overhead.

Finally, we make a statement related to our observations when different sector sizes are applied to the network. We investigated the performance of three different sector sizes,
3, 4, and 5 sectors. This is particularly of interest when a high density WLAN must be designed using sector antennas. An increased number of sectors can significantly increase the theoretical throughput. However, in practical deployments it is necessary to consider how directional beams may lead to overheard protocol management frames. In addition, a potential threat in omi-directional wireless systems is the broadcast in wireless networks. Wireless terminals in distinct sectors may hear the management frames, but are unable to respond. Hence, further research is needed how a radio resource management (RRM) must be configured to benefit from the effectiveness of the sectorization. Fig. 5 shows the result when different sector sizes are used for retransmission threshold \( r_{\text{thres}} = 3 \). Fig. 6 shows the result for \( r_{\text{thres}} = 6 \).

VII. CONCLUSIONS

In this paper, a novel spatial orthogonal access management scheme was proposed. It allows the improvement of the average transmission performance in highly dense IEEE 802.11ah WLANs. The main feature of the proposed method is a sector-based RTS/CTS access scheme, which significantly reduces RTS frame collisions. The RTS frame collisions can be reduced by scheduling the RTS frame invocation for each sector that is spatially orthogonal. It was verified that the proposed method considerably reduces the RTS frame collisions and improves the throughput in highly dense WLANs. Performance analysis and simulation results have proven that the proposed sectorized RTS/CTS access scheme allows higher average throughput compared to the legacy media access management schemes. With the proposed RTS/CTS access scheme a significant larger number of wireless stations can access the wireless network with a reduced collision probability; thus, increasing the network size by the factor 5.5. This is particularly true for different network traffic scenarios, including small data packets (IoT, M2M, smart meter) as well as large data packets (big data pipe). Next, we will focus on the reduction of mutual interference amongst APs while using the proposed access scheme and we will pursue the implementation of spatial orthogonal beam forming in our multi-antenna array MIMO-OFDM sub-1 GHz testbed.

REFERENCES