New Throughput Analysis of Long-Distance IEEE 802.11 Wireless Communication System for Smart Grid

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Abstract—**The use of wireless access networks, particularly IEEE 802.11 wireless access networks, is an economical method for realizing a communication network between a core information network of a smart grid and a rural area network. This paper presents a novel analysis of the throughput performance of the IEEE 802.11 carrier sense multiple access with collision avoidance (CSMA/CA) protocol with a large propagation delay. The throughput analysis is performed by using a real model. A Markov chain model is used to analyze the throughput performance of the IEEE 802.11 CSMA/CA binary exponential backoff algorithm. The results of analysis and computer simulations show that the theoretical throughput is in good agreement with the throughput obtained from computer simulations under the propagation delay less than 20 μs. When the propagation delay is more than 20 μs, the throughput obtained from the simulation results becomes larger than the theoretical throughput because of short-term unfairness. The throughput degradation for a transmission rate of 6 Mb/s and a propagation delay of 40 μs is 16.8 %; this propagation delay corresponds to a transmission distance of 12 km.**

Keywords-component; CSMA/CA; IEEE 802.11; propagation delay; long-distance; smart grid; throughput

I. INTRODUCTION

The electric power industry is undergoing rapid changes. The rising costs of energy and climate change are the major reasons for these changes. A smart grid is expected to be a promising electric power system that can generate, transmit, and distribute electricity ecologically and economically by employing an extensive data communication system [1]. Wireless local area networks (WLANs) are broadband and low-cost communication networks, and hence, WLAN technologies have significant advantages over traditional communication technologies that are used in current conventional electric power systems. Thus far, most WLAN applications have been limited to small areas such as homes and offices. In this paper, we try to apply WLAN technologies to a long-distance communication access system for use in a smart grid in rural areas. It is not cost-effective to connect rural and isolated areas with a smart grid core communication network by using wired access networks such as those based on optical fibers and power line communications and so on. To increase the use of wireless networks, the Federal Communications Commission (FCC) of the U.S. Government announced "Super WiFi" in September, 2010; Super WiFi will be used in the UHF band to increase the cell size of WLANs [2]. The use of IEEE 802.11 wireless access networks is a very cost-effective method of connecting the rural and isolated areas with the urban areas.

The IEEE 802.11 distributed coordination function (DCF) employs one of the most popular medium access control (MAC) protocols used in WLANs. It is a CSMA/CA protocol. The IEEE 802.11 DCF is usually applied to networks that have a range of up to a few hundred meters. However, it is advantageous to use it for long-distance access, moreover it can operates in unlicensed spectra such as the 2.4 and 5 GHz bands. Mishra et al. presented the case which employed WiFi and CDMA networks for economically viable networks in rural developing regions [3]. Clark et al. evaluated the effect of path loss and multipath dispersion on the performance of IEEE 802.11 radio design [4]. Leung et al. showed that CSMA/CA performance is slightly degraded in the case of an IEEE 802.11 DCF network with a cell size of 6 km, when compared with the performance of a 600 m WLAN [5].

Bianchi proposed an analytical Markov chain model with unlimited frame retransmission to compute the IEEE 802.11 DCF throughput in traffic saturation conditions [6]. Wu et al. proposed a modified Bianchi's model with limited frame retransmission [7]. Lopez-Aguilera et al. extended Bianchi's analytical model for use in long-distance transmission. They analyzed the relationship between a slot time and a propagation delay and presented the effects of propagation delay on the system throughput [8]. However, it has been found that their analytical results are not in agreement with the results obtained by QualNet 4.5.1 which is network evaluation software [9], [10]. This is because Lopez-Aguilera et al. assumed that both the backoff counter start timings of two WLAN stations are synchronized, whereas those of QualNet 4.5.1 are not. This paper proposes an analytical model for evaluating the effects of propagation delay on the system throughput of unsynchronized slot systems. This model is a realistic one for analyzing WLANs based on the IEEE 802.11 DCF standard. The results of Markov chain analysis and computer simulations show that the theoretical throughput is in good agreement with the throughput obtained from computer simulations.

The rest of this paper is organized as follows: In section II, the system model that we consider is presented. In section III, we analyze system throughput performances based on the proposed system model. In section IV, we show the results of computer simulations and compare them with theoretical values. We present the conclusions in section V.

II. System Model

Let us consider a system model with a point-to-point long-distance wireless connection, as shown in Fig. 1. The wireless station (STA) shown in Fig. 1 has a single IEEE 802.11 interface and a single directional antenna for reducing a multi-path delay spread and obtaining a high antenna gain. The MAC scheme is operated with the IEEE 802.11 DCF. STAs A and B attempt to exchange data frames. A frame is transmitted from one STA and it reaches another STA after a propagation delay. A collision occurs if the destination STA starts transmitting a frame before it senses the frame transmitted from the source STA. Otherwise, the frame is received successfully, and the destination STA then transmits the ACK frame. The PHY layer complies with the IEEE 802.11a standard in the 5 GHz band [11]. This standard is based on the orthogonal frequency division multiplexing (OFDM) modulation scheme. The maximum MAC payload size is assumed to be 1,500 bytes, and the PHY transmission rate is selected from the range 6–54 Mb/s, according to the wireless channel condition. It is assumed that the offered traffic of STAs A and B is saturated (i.e., the transmission queues of STAs A and B are always nonempty) and that the size of the transmission queues of both STAs is infinite. Moreover, it is assumed that any STA in the receiver mode can sense frames transmitted from the other STA and the capture effect does not occur (i.e., all STAs cannot obtain any information at the instant a frame collision occurs). The frame error probability caused by thermal noise and interference signals is assumed to be negligible.

Let us consider the discrepancy in the start times of the slots between the STAs, as shown in Figs. 2 and 3. Figure 2 shows the synchronized slot model, which was included in the conventional analysis model [8]. We propose to use an unsynchronized slot model for analyzing the system throughput performance, as shown in Fig. 3. When STA B transmits an ACK frame, the discrepancy in the end time of ACK transmission and reception is equal to the propagation delay δ and hence, the start times of both the backoff counters are inconsistent. The conventional model assumes that STAs A and B reset the start timings of the backoff counters when a DIFS period has elapsed after the reception of the ACK frame. The start timings of the backoff counters of both STAs A and B are then synchronized by eliminating δ. On the other hand, in the unsynchronized slot model shown in Fig. 3, no slot alignment for synchronizing the start timings of the backoff counters to eliminate δ is performed; that is, the start timing of

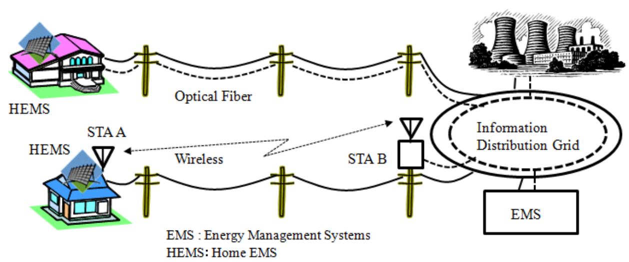

Fig. 1. A long-distance wireless access network with the IEEE 802.11 DCF.

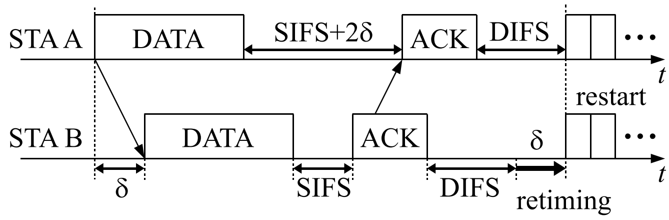

Fig. 2. Synchronized slot model with CSMA/CA protocol.

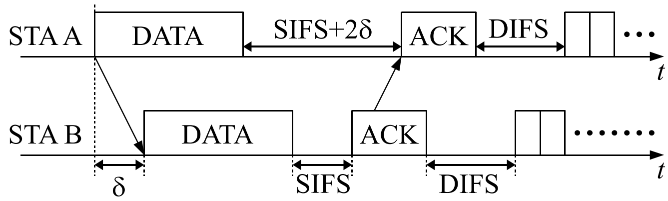

Fig. 3. Unsynchronized slot model with CSMA/CA protocol.

STA A is not synchronized with that of STA B.

Let us investigate whether the probability of data frame collision increases with a propagation delay δ. The CCA time, RX-to-TX turnaround time, and MAC protocol processing time are represented by ε_1, ε_2, and ε_3, respectively [11]. The total processing time is expressed as $\varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3$. An STA cannot sense any frame within the time ε, just before the STA attempts to start transmitting a frame. In this paper we assumed that the values of ε_1, ε_2, and ε_3 are 2 μs, 1 μs, and 1 μs, respectively. Let us assume that both the STAs share ε_1, ε_2, and ε_3. The slot time is denoted as σ whose value is 9 μs according to the IEEE 802.11a standard.

The mechanism of data frame collision for different propagation delays is shown in Fig. 4. In this figure, TX-STA is defined as the STA that succeeded in just previous data frame transmission and RX-STA is the STA that succeeded in just previous data frame reception. In Fig. 3, STA A becomes TX-STA and STA B becomes RX-STA after this data frame transmission. TX-STA receives an ACK frame from RX-STA after a propagation delay. Therefore, the data frame transmission from TX-STA starts with a propagation delay. Let us consider that the propagation delay δ is in the range $M\sigma < 2\delta + \varepsilon < (M + 1)\sigma$, for an integer $M \geq 0$. If M is equal to 0, i.e., $0 < 2\delta + \varepsilon < \sigma$, data frames collide with each other when STAs transmit the data frames in the same k-th slot, as shown in Fig. 4. In contrast, if M is positive, i.e., STAs are more distant from each other, there are $M + 1$ consecutive slots within the

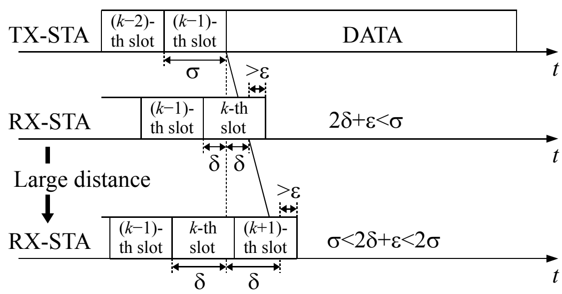

Fig. 4. Collision mechanism for several propagation delays.

collision region. Figure 4 shows the collision mechanism for $M = 1$. Thus, the probability of data frame collision increases with increasing the propagation delay.

III. THROUGHPUT ANALYSIS

The system throughput of the point-to-point radio model with the IEEE 802.11 DCF is analyzed. The analysis is divided into two distinct parts. First, we analyze the behavior of a single STA with the Markov chain [6], and we obtain data frame transmission probabilities and conditional collision probabilities of data frames. Second, by considering the events that can occur within a generic (i.e. randomly chosen) slot time, we introduce the system throughput that is expressed for any given propagation delay.

A. Markov Chain Model

Let $b(t)$ be a stochastic process of the backoff time counter for an STA. The backoff counter is randomly chosen with a uniform distribution in $[0, W_i - 1]$ at the i-th backoff stage just after the previous frame has successfully been transmitted or has been collided, where $W_i = 2^i W$ for $0 \leqslant i \leqslant m$. The value $(W-1)$ is called the minimum contention window. The value of m is called the maximum stage number. If a frame has successfully been transmitted, the backoff stage number i is reset to 0; if the frame has collided, i becomes a new value $i \in min\{i + 1, m\}$ and the frame will be retransmitted. Let $s(t)$ be the stochastic process representing the backoff stage $(0,\ldots,m)$ of the STA at time t. The key approximation in Bianchi's analytical model is that at each transmission, the collision probability of each frame is constant and independent, regardless of the number of retransmissions. Thus, it is possible to model the bidimensional process $(s(t), b(t))$ with a discrete-time Markov chain, where $B_k^i = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}$, $i \in [0, m]$ and $k \in [0, W_i - 1]$ denotes the stationary distribution of the chain. The expression for the original Bianchi's Markov chain model is based on unlimited data frame retransmission. Wu modified this model by adopting limited data frame

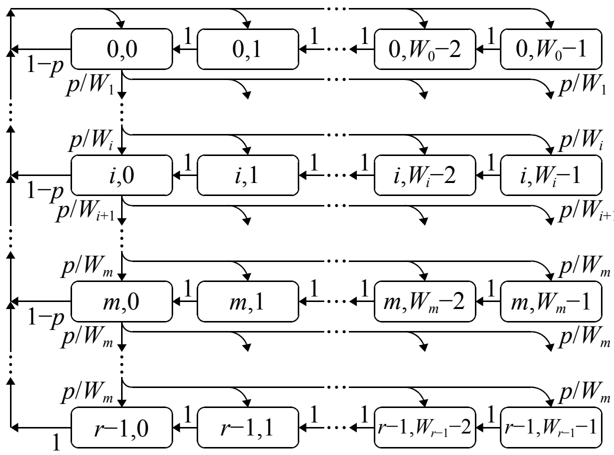

Fig. 5. Modified Markov chain model of the backoff stage and backoff counter, in which the number of re-transmission is limited.

In Fig. 5, the modified Bianchi's analytical model with m and r is shown, where the value of r is the number of data frame retransmissions. For simplicity, we assumed that $r = m+1$. By solving the Markov chain model shown in Fig. 5, the probability τ that an STA transmits a data frame in a randomly chosen slot time, is obtained as follows:

$$\tau = \frac{2\sum_{i=0}^{r-1} p^i}{\sum_{i=0}^{r-1} p^i + W \sum_{i=0}^{r-1} (2p)^i}, \tag{1}$$

where p is the conditional collision probability.

When an STA transmits a data frame just after the slot time has elapsed, the collision-free probability is given by the probability that another STA does not transmit data frames during the $(M + 1)$-th slot time. This collision-free probability is expressed as

$$1 - p = (1 - \tau)^{M+1}. \tag{2}$$

By solving the nonlinear simultaneous equations (1) and (2) numerically, we obtain the transmission probability τ and the conditional collision probability p at each slot time.

B. Throughput Evaluation

In the case of an unsynchronized slot model for any given propagation delay, the aggregate system throughput S in IEEE 802.11 DCF networks can be calculated on the basis of TX-STA timing events. The events of successful data frame transmission are divided into events of successful TX-STA transmission and successful TX-STA reception. The modified Bianchi's analytical model evaluates the normalized value of the aggregate system throughput S as the fraction of time during which the channel is used to transmit data bits successfully. Let E_s denote the average length of variable length slot time, which consist of slots in which successful transmission occurs, slots in which collision occurs, and empty slots.

Let P_σ be the probability of an empty slot where STAs A and B do not transmit at the same time. P_σ is expressed as

$$P_\sigma = (1 - \tau)^2. \tag{3}$$

The probability $P_{TX,tx}$ of a successful transmission by TX-STA is expressed as

$$P_{TX,tx} = \tau(1 - \tau)^{M+1}. \tag{4}$$

As shown in Fig. 6, this probability is obtained from the probability that RX-STA does not transmit a data frame during $(M+1)$ slot times when TX-STA starts to transmit a data frame. The probability $P_{TX,rx}$ of a successful transmission by RX-STA in the channel is expressed as

$$P_{TX,rx} = \tau(1 - \tau). \tag{5}$$

As shown in Fig. 7, this probability is obtained from the probability TX-STA does not transmit a data frame during a slot time when RX-STA starts to transmit a data frame. The probability P_C of a frame collision during transmission is obtained as

$$\begin{aligned} P_C &= 1 - P_\sigma - P_{TX,tx} - P_{TX,rx} \\ &= \tau\left(1 - (1-\tau)^{M+1}\right). \end{aligned} \quad (6)$$

The average length of a slot time E_s is obtained as

$$E_S = P_\sigma \sigma + P_{TX,tx} T_{TX,tx} + P_{TX,rx} T_{TX,rx} + P_C T_C, \quad (7)$$

with

$$T_{TX,tx} = DATA + \delta + SIFS + \delta + ACK + DIFS, \quad (8)$$

$$T_{TX,rx} = DATA + SIFS + ACK + \delta + DIFS, \quad (9)$$

$$T_C = DATA + ACK\ Timeout + DIFS, \quad (10)$$

where $T_{TX,tx}$ is the duration between the start time of the data frame transmission by TX-STA and the end time of the *DIFS* period of TX-STA, $T_{TX,rx}$ is the duration between the start time of the data frame reception by TX-STA and the time after the passage of the *DIFS* period of RX-STA. The average busy time in the case of a frame collision is shown in Fig. 8; T_C is the time for which both STAs consider the channel to be busy after collision. *ACK Timeout* is the waiting time limit for ACK frames.

The normalized value of the system throughput S is expressed as

$$S = \frac{R\left(P_{TX,tx} + P_{TX,rx}\right)DATA}{E_S}, \quad (11)$$

where *DATA* is the size of the data frame payload and R denotes the data transmission rate (Mb/s).

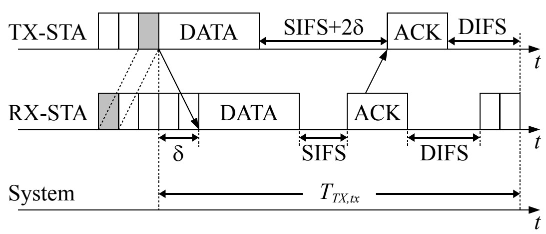

Fig. 6. Channel busy period ($T_{TX,tx}$) in the case of a successful transmission by TX-STA.

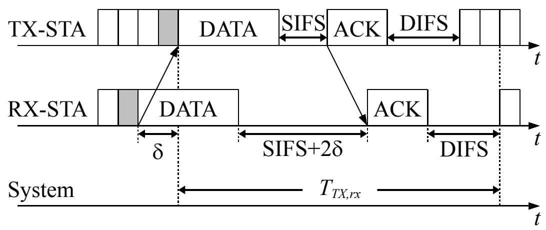

Fig. 7. Channel busy period ($T_{TX,rx}$) in the case of a successful reception by TX-STA.

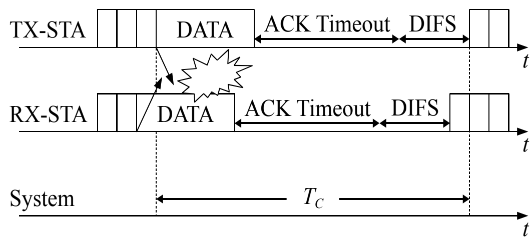

Fig. 8. Channel busy period (T_C) in the case of a frame collision.

IV. Simulation Results

The performance of our approximate model is evaluated at transmission rates of 6 and 24 Mb/s for the same parameters as those of the IEEE 802.11a standard. The major system parameters used in the analysis and simulations are listed in Table 1. The variable *DATA* that appears in (8), (9), and (10) is derived as follows:

$$DATA = 20\ \mu s + 4\ \mu s \times \left\lceil \frac{16 + (30 + D) \times 8 + 6}{L_{OFDM}} \right\rceil. \quad (12)$$

L_{OFDM} denotes the number of bits per OFDM symbol; $\lceil x \rceil$ is the ceiling function that is the smallest integer not less than x.

Figure 9 shows the simulation results for the proposed unsynchronized slot model with CSMA/CA protocol which are consistent with the results obtained by QualNet 4.5.1 [9], and numerical results calculated using the conventional synchronized slot model. The propagation delay δ is plotted on the horizontal axis and is in the range of 1–50 μs. These values of δ correspond with transmission distances in the range of 0.3–15 km. The system throughput is plotted on the vertical axis. The values of δ that result in performance degradation are

Table 1. Major system parameters used in the analysis and simulations.

MAC payload *D*	1500 bytes
MAC header	26 bytes
FCS	4 bytes
PHY header	20 μs
Tail bit	6 bits
Service bit	16 bits
ACK length	20 μs + 134 bits
OFDM symbol length	4 μs
Number of bits per OFDM symbol,	
L_{OFDM} (6 Mb/s)	24 bits
L_{OFDM} (24 Mb/s)	96 bits
Slot time, σ	9 μs
SIFS	16 μs
DIFS	34 μs
ACK Timeout	83 μs + ACK length
Propagation delay δ	1–50 μs
Minimum size of contention window	15
Maximum value of backoff stage, *m*	6
Maximum size of contention window	1023
CCA time, ε_1	2 μs
RX-to-TX turnaround time, ε_2	1 μs
MAC process time, ε_3	1 μs

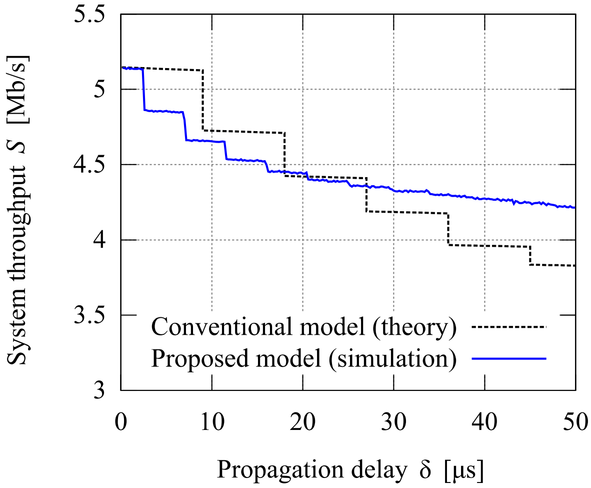

Fig. 9. System throughput degradation with increasing propagation delay for conventional and proposed models.

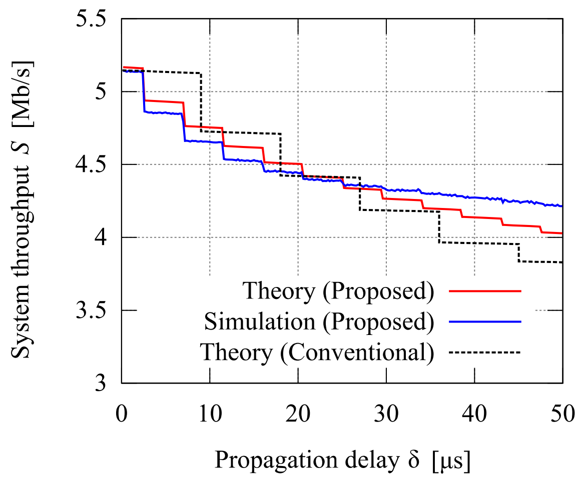

Fig. 10. System throughput degradation with increasing propagation delay for transmission rate of 6 Mb/s.

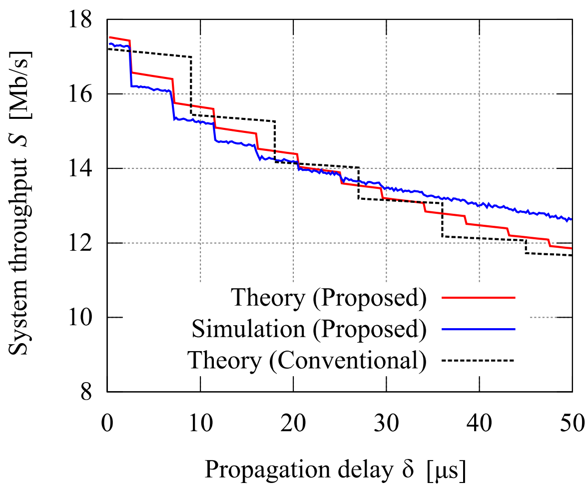

Fig. 11. System throughput degradation with increasing propagation delay for transmission rate of 24 Mb/s.

less than those obtained by Lopez-Aguilera et al. This implies that when δ is less than 20 µs, the system throughput performance of a real unsynchronized slot model is degraded in comparison with that of the conventional model.

In Fig. 10 and 11, the system throughput performance is plotted against δ for three cases i.e., simulation results and theoretical results obtained using the proposed real unsynchronized slot model, and numerical results calculated using the conventional model at transmission rates of 6 and 24 Mb/s. We found that the system throughput deteriorates for propagation delays of 2.5, 7, 11.5, 16, 20.5, 25, 29.5, and 34 µs. The larger the hardware-dependent RX-to-TX turnaround time, CCA time, and MAC processing time, the lower the propagation delays that result in performance degradation. The system throughput degradations for a transmission rate of 6 Mb/s are 5.5 % at δ = 4 µs, 14.4 % at δ = 22 µs, and 16.8 % at δ = 40 µs. The system throughput degradations for a transmission rate of 24 Mb/s are 6.4 % at δ = 4 µs, 19.6 % at δ= 22 µs, and 24.8 % at δ = 40 µs.

When δ is less than 20 µs, the theoretical throughput is in good agreement with the throughput obtained from simulations. However, when δ exceeds 20 µs, the theoretical throughput is less than that obtained from simulations. This is because there is an imbalance between the transmission opportunities for two STAs; this imbalance causes a phenomenon that we call "short-term unfairness." Figure 12 shows the backoff stage transition at each propagation delay in the rage of 1–50 µs. In the case of δ=1 µs, there are no imbalance data frame transmissions between two STAs. However, in the cases of δ=30 and 50 µs, there are many imbalance data frame transmissions during a short period. The simulation results obtained under this "short-term unfairness" for δ= 50 µs are shown in Fig.13. The figure shows that the data frame transmission from STA B is dominant because of the short-term unfairness during this period. When the value of the backoff stage of STA A remains large, the value of the backoff stage of STA B occasionally remains small. In such situations, STA B for which the backoff

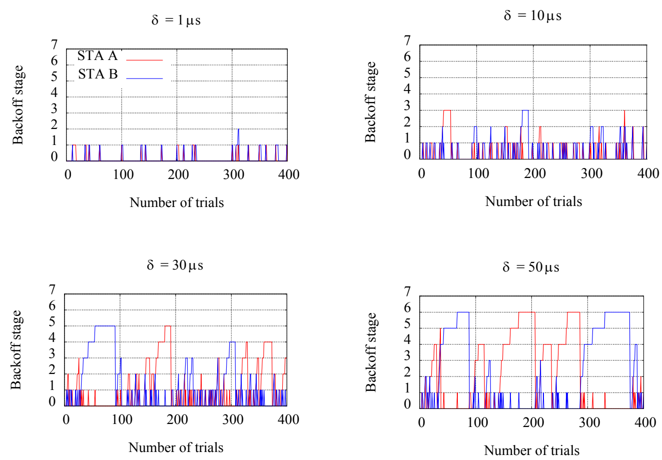

Fig. 12. Backoff stage transition at each propagation delay.

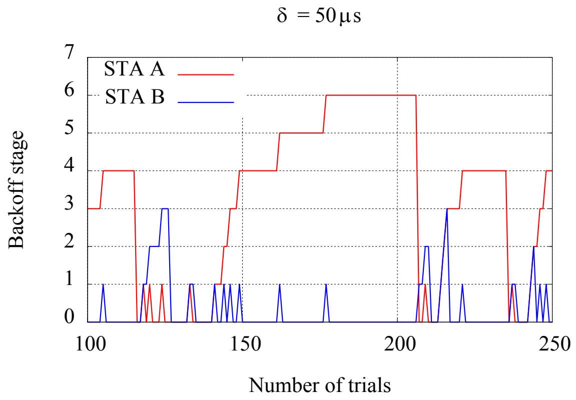

Fig. 13. Backoff stage transition for δ of 50 μs.

stage has a smaller value can transmit data frames successively without data frame collisions. Therefore, short-term unfairness contributes to the increase of the system throughput.

V. CONCLUSION

We have performed the first throughput analysis of the effects of a propagation delay on long-distance wireless access networks that use the IEEE 802.11 DCF protocol without slot synchronization, and we have calculated the total throughput for different propagation delays from 1–50 μs by Markov chain analysis and computer simulations. When the propagation delay is less than 20 μs, the theoretical throughput is in good agreement with the throughput obtained from computer simulations. The total throughput deteriorates for propagation delays of 2.5, 7, 11.5, 16, 20.5, 25, 29.5, and 34 μs. These values are less than that obtained by Lopez-Aguilera et al. because the slots are not synchronized with both the STAs. When the propagation delay is more than 20 μs, the system throughput obtained from the simulation results becomes larger than the theoretical system throughput because of short-term unfairness.

The system throughput degradation for a transmission rate of 6 Mb/s and a propagation delay of 40 μs is 16.8 % at the most; this propagation delay corresponds to a transmission distance of 12 km. We demonstrated that IEEE 802.11 WLAN is one of the promising technologies, even for long-distance communication access networks for use in a smart grid.

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