PAPER

Optimal Ranging Algorithms for Medium Access Control in Hybrid Fiber Coax Networks

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SUMMARY The ranging algorithm allows active stations to measure their distances to the headend for synchronization purpose in Hybrid Fiber Coax (HFC) networks. A practicable mechanism to resolve contention among numerous stations is to randomly delay the transmission of their control messages. Since shorter contention cycle time increases slot throughput, this study develops three mechanisms, fixed random delay, variable random delay, and optimal random delay, to minimize the contention cycle time. Simulation demonstrates that the optimal random delay effectively minimizes the contention cycle time and approaches the theoretical optimum throughput of 0.18 from pure ALOHA. Furthermore, over-estimation reduces the impact on contention cycle time more than under-estimation through sensitivity analysis, and both phenomenon damage slot throughput. Two estimation schemes, maximum likelihood and average likelihood, are thereby presented to estimate the number of active stations for each contention resolution round. Simulation proofs that the proposed estimation schemes are effective even when the estimated number of active stations in initial contention round is inaccurate.

key words: *ranging, contention resolution, throughput, estimation*

1. Introduction

Hybrid Fiber Coax (HFC) technology provides coaxial networks with two-way and broadband transmission capabilities. To make cable modems and headends designed by different vendors interoperable, two standards, *IEEE 802.14* [1] and *Data-Over-Cable Service Interface Specifications* (DOCSIS) [2] specifying Physical and Medium Access Control (MAC) layers have been developed. A two-way HFC network is a point-to-multipoint, tree-and-branch access network in the downstream direction, but a multipoint-to-point, bus access network in the upstream direction. Since a station cannot independently detect upstream collisions, it should not send data at will; otherwise, the performance will be significantly impacted by serious collisions. Therefore, all upstream data transmission should be centrally coordinated by the headend. For effective functioning, each station should synchronize with the headend. Owing to the typically large propagation delay in the HFC networks, each station should learn its distance from the headend and compensate for this distance such that all stations and the headend have a consistent system-wide view of time. Therefore, a *ranging process* is presented to measure the distance between a station and the headend. Collisions occur when multiple active stations simultaneously transmit ranging messages on a slot. Consequently, each collided message must be retransmitted round by round until it is successfully received.

The random delay mechanism is proposed to randomly delay the transmission of the ranging messages and reduces the probability of collisions. To minimize the average time of a ranging process, three algorithms are developed to calculate the optimal random delay. Since the headend can determine the size of the ranging area, the proposed mechanism is applicable to HFC networks. Furthermore, two estimation schemes for the number of active stations in each round except the initial one are also proposed to effectively adjust the random delay in each round. Many ranging algorithms have been developed for different applications [3]–[5] but were presented to estimate the *point-to-point* distance. Therefore, those algorithms cannot be directly applied in the HFC environment.

The rest of this paper is organized as follows. Section 2 gives the statement of the ranging problem and describes the system model. Meanwhile, Sect. 3 proposes a number of algorithms and compares their throughput via simulation and analysis. Section 4 then discusses the implementation issues, including sensitivity analysis and estimation schemes for the number of active stations. Finally, Sect. 5 summarizes this study.

2. Problem Statement

Figure 1 shows how a ranging process performs. If the headend sends a ranging message, M, to invite each station to transmit a message which should arrive at the headend at T_1, then the headend needs to send M no later than $T_1 - T_X$, so that every station can receive

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M and make a timely response. T_X denotes the maximum round-trip propagation delay defined in the HFC network. In Fig. 1, station A receives M at T_{A1}. If station A sends its response immediately, the response will arrive at the headend at T_2 instead of at T_1. The idea is that station A has to wait its Round-Trip Correction time, RTC_A, and then send the response, so that the response arrives at the headend at exactly T_1. RTC_A is therefore calculated as $T_X - T_A$. The headend must help station A to calculate its own round-trip delay, T_A, so that station A can adjust its transmission starting time to achieve MAC level synchronization. The general steps of the ranging process in DOCSIS is listed below and shown in Fig. 2:

1. Obtain global timing reference: After being powered up, the station should listen to the *sync* message sent periodically by the headend at an interval of tens of milliseconds. Upon receiving *sync* message, the station should then set its local clock to the time in the sync message. After "syncing" several times, the station's clock rate can be synchronized to the clock rate of the headend, as in step (b).
2. Identify the ranging area: The headend also periodically broadcasts a *ranging invitation* message to invite all unranged stations to join the network. The starting point of the ranging area is described by explicitly identifying the starting minislot number in the bandwidth allocation message, *MAP*. The headend must make the ranging area sufficiently large to accommodate the possible long propagation delay from the stations.
3. Transmit the ranging message: The ranging process consists of initial ranging and station ranging. After determining the ranging area, the station attempts to obtain a temporary service identifier to facilitate other initialization operations in initial ranging, and the station uses the station maintenance area to perform periodical ranging. Similarly, the headend may calculate the timing offset for station A as $T_5 - T_4$. The adjustment parameters are sent back to station A through the ranging response message.
4. Make adjustments according to the feedback message: The station is roughly ranged after adjusting its parameters including timing offset, power level, frequency offset, and center frequency, according to the values offered in the feedback message, as in steps (d) and (e). The ranging process is repeated until the headend considers that the station requires no more adjustment.

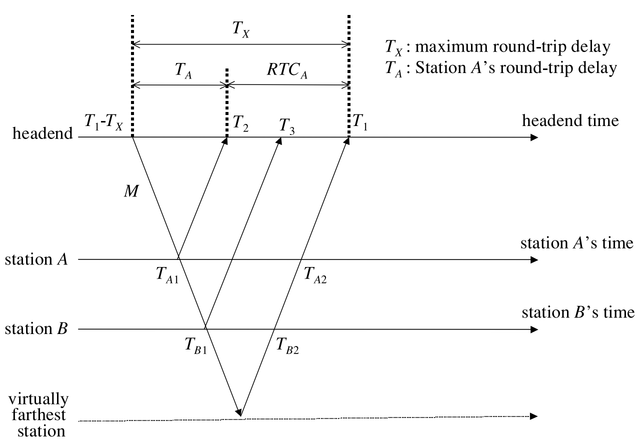

Fig. 1 Normal ranging process.

This study seeks to minimize the average time of a ranging process and thus enhances slot throughput, which is defined as the ratio of the number of involved stations over the average time of a ranging process. The mecha-

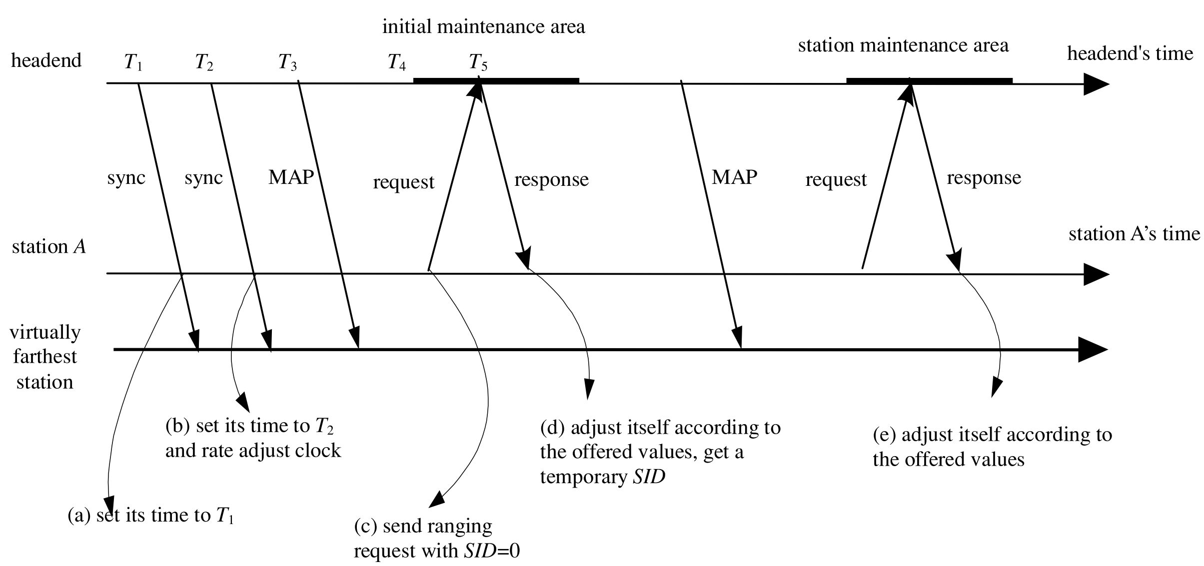

Fig. 2 The DOCSIS ranging process.

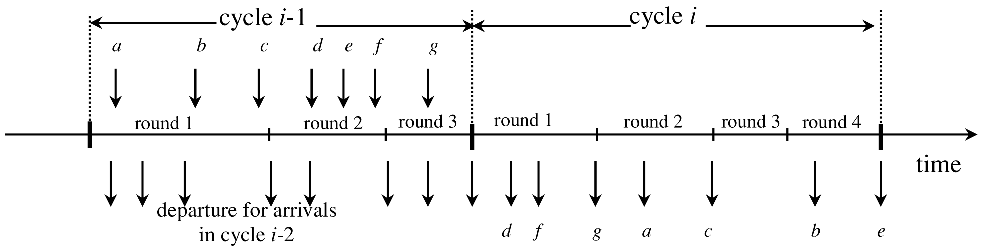

Fig. 3 A contention cycle with blocked arrivals.

nism employed for resolving contention among numerous stations is to randomly delay the transmission of their control messages. The system involves a finite-population stations and a blocked-access scheme where stations that are activated in the current contention resolution cycle are prohibited from participating in this contention cycle.

Figure 3 illustrates the aforementioned contention resolution process. A contention cycle consists of several contention rounds that completely resolve a group of unranged stations. A contention round corresponds to the maintenance area in Fig. 2. Notably, the maintenance area exists in upstream and the time intervals between consecutive maintenance areas are allocated to ranged stations for data transmission. Moreover, this study focus on contention slots throughput instead of overall upstream bandwidth throughput. Therefore, those time intervals for data transmission are disregarded in average cycle time evaluation. Assume that when the system is in the contention resolution cycle i-1, stations a, b, c, d, e, f and g become active. All these active stations are serviced in the next cycle, cycle i. In round 1 of cycle i, each active station must wait for a random delay before it begins transmitting its ranging message, which is assumed to have a length of 1 unit. The range of random delay in round 1 is between 0 and the duration of round 1. In this illustration, the result of round 1 is that stations d, f, and g successfully transmit their ranging messages, but the transmissions of the other stations fail due to collisions. Stations a, b, c and e will thus continue the ranging process, contention resolution process, in the next round of cycle i until all of the active stations have successfully transmitted their ranging messages. In this illustration, the 7 active stations require 4 rounds in cycle i to complete the ranging process.

Notably, the range of the random delay employed in each contention round may subtly influence the cycle time. A long random delay results in a long round time, but increases the probability of successful message transmission as well as the probability of a contention cycle containing a small number of rounds. On the other hand, a short random delay reduces round time but increases the number of rounds in a contention cycle owing to frequent collisions. Consequently, to minimize the cycle time, the range of random delay in each round should be selected carefully.

3. Random Delay Algorithms

To resolve contention efficiently, three algorithms are proposed to calculate the random delay in each contention round based on the number of contending stations to minimize the average cycle time. These algorithms are for headend to allocate size of maintenance area effectively; therefore, no modification on DOCSIS protocol is needed.

3.1 Fixed Random Delay: FRD

This algorithm assumes that the number of active stations is given and a *fixed* random delay for each contention round is employed throughout the contention cycle. The fixed random delay is calculated from a state transition diagram depicted in Fig. 4. This state transition diagram defines states as the number of active stations in a round. The contention is assumed to initially involve n active stations. Meanwhile, the transition from State i to State $i-j$ means that j stations successfully transmit their packets among i active stations; therefore, the remaining $i-j$ stations must contend in the following rounds. The probability of this transition is denoted by $p(i,j,d)$ given the random delay is d and is calculated by exhaustive simulation. A resolution scenario is defined as consecutive states from initial state to state 0 in a contention cycle. For each d, the average cycle time is obtained from

$$\begin{aligned} ACT_{d_n} = \; & d * p(n,n,d) \\ & +2d * [p(n,n,d)p(n,0,d) \\ & + \sum_{i=1}^{n-2} p(n,i,d)p(n-i,n-i,d)] \\ & \ldots \\ & \ldots \\ & +Kd * \sum_{j} (\text{probability of a resolution} \\ & \quad \text{scenario } j \text{ with cycle time } Kd) \end{aligned}$$

where K is determined if the sum of probabilities of resolution scenarios with cycle time $(K+1)d$ is less than 10^{-5}. Therefore, a d with minimal average cycle

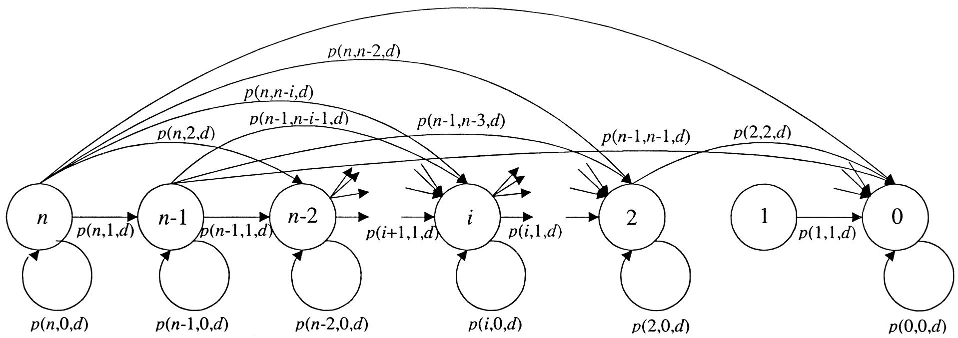

Fig. 4 State transition diagram for developing FRD.

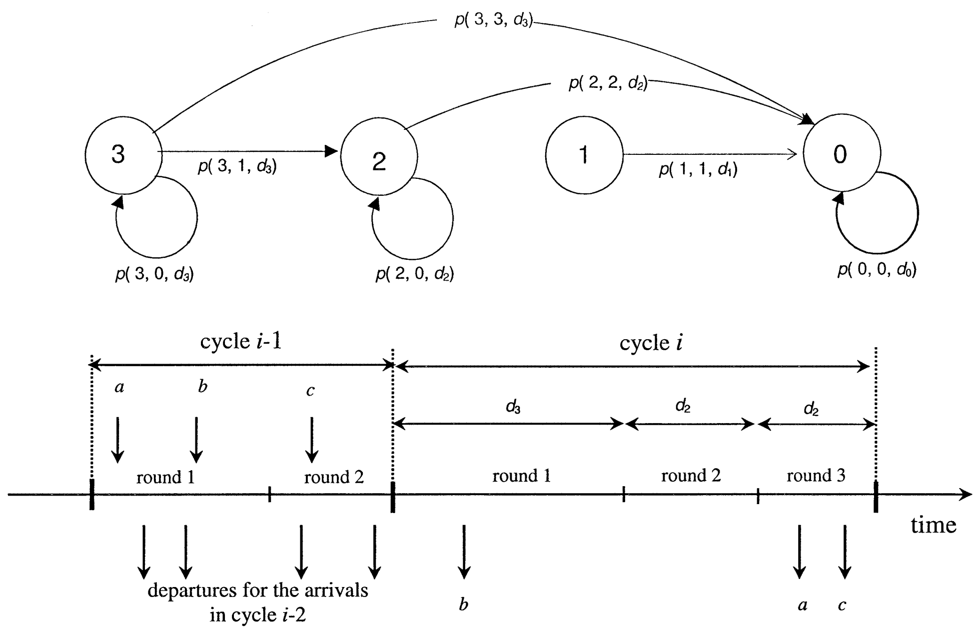

Fig. 5 State transition diagram for VRD.

time is chosen as random delay in each contention round given n initial active stations, d_n.

3.2 Variable Random Delay: VRD

VRD stands for *variable* random delay for each round thus minimizing the average cycle time. In each contention round, the random delay corresponds to that in initial state in FRD. For example, if there are k active stations in a contention round, the random delay in that round is set to d_k. The length of each round can thereby be dynamically controlled. Figure 5 illustrates the contention resolution process adopting the VRD mechanism. There are three active stations involved in the first round of cycle i; thus, the round time is d_3. One active station successfully transmits its control message in this round, therefore, the round time for the second round is set to d_2. Since no active station successfully transmits its control message, the round time of the third round must be equal to d_2. All active stations after round 3 have been successfully resolved. If FRD is used, the cycle time of cycle i is $d_3 + d_3 + d_3$. However, by adopting VRD, the cycle time of cycle i is reduced to $d_3 + d_2 + d_2$. Since VRD considers random delay round by round, it intuitively outperforms FRD, in which random delays of rounds other than the first round cannot be determined dynamically based on the contention results.

3.3 Optimal Random Delay: ORD

ORD involves a globally optimal random delay for different numbers of active stations in each round thus minimizing the average cycle time. The bottom-up approach is adopted herein to derive optimal variable random delay for each round. $d_{i,OPT}$ is denoted as the globally optimal value of d for each $p(i, j, d)$ in Fig. 4 to minimize the average cycle time. Consequently, all $d_{i,OPT}$'s are calculated as follows:

1. $d_{0,OPT} = d_{1,OPT} = 0$.

2. $d_{2,OPT}$ denotes the optimal value of d that minimizes the average cycle time modeled by Fig. 6. For each d, the average cycle time is obtained from

$$ACT_{d_2} = \sum_{i=1}^{K} \left[i * d * p(2,0,d)^{i-1} p(2,2,d) \right],$$

where K is determined if the sum of probabilities of resolution scenarios with cycle time $(K+1)d$ is less than 10^{-5}.

3. $d_{3,OPT}$ denotes the optimal value of d that minimizes the average cycle time modeled by Fig. 7. For each d, the average cycle time is obtained from

$$ACT_{d_3} = \sum_{i=1}^{K} p(3,0,d)^{i-1} [i * d * p(3,3,d) + ACT_{d_{2,OPT}} * p(3,1,d)],$$

where K is determined if the sum of probabilities of resolution scenarios with cycle time $(K+1)d$ is less than 10^{-5}.

4. $d_{4,OPT}$, and so on, can be calculated by the iterative procedure as above.

3.4 Numerical Observation

Three random delay algorithms are conducted via simulation. Without losing generality, the time resolution is 10^{-4} unit to approximate continuous, i.e., unslotted, behavior of transmitting ranging messages. Moreover, this study only simulates the ranging contention resolution process instead of overall upstream transmission behavior. Hence, no network parameters are considered. Although after receiving several sync messages, one station might align to slot boundary at the station side. However, it is very likely for a station's message to collide with other station's messages at the head-end side without learning its RTC. Therefore, considering the propagation delay, it makes sense to treat the upstream ranging process as an unslotted system throughout the ranging process. Its behavior can hence be modeled as a pure ALOHA system.

Figures 8 and 9 display the average cycle time and slot throughput, respectively, for the proposed random delay algorithms. Since FRD lacks the flexibility to adjust the random delay round by round, average cycle time is the longest among all. Additionally, by systematically calculating the value of random delay for a given number of active stations ORD produces a shorter average cycle time than VRD. Regarding slot through-

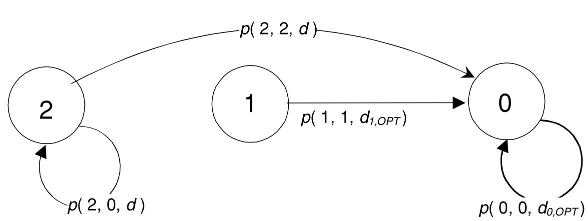

Fig. 6 State transition diagram for ORD to calculate $d_{2,OPT}$.

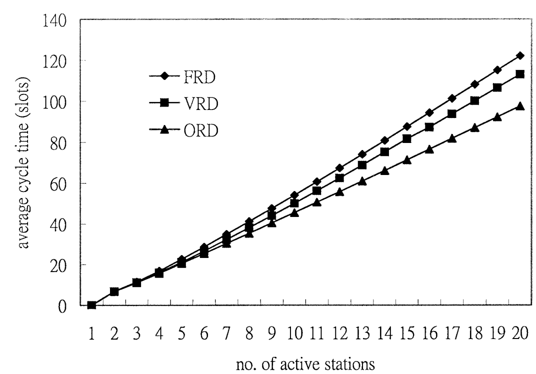

Fig. 8 Average cycle time for FRD, VRD, and ORD algorithms.

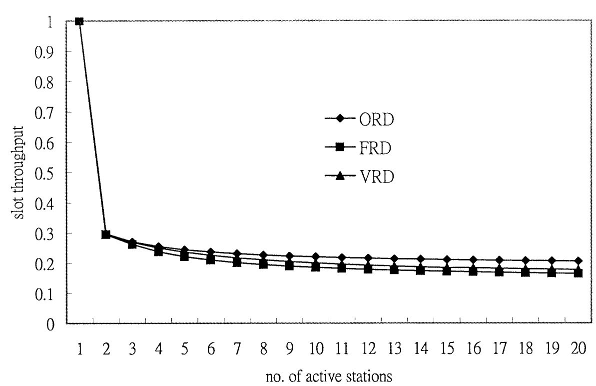

Fig. 9 Slot throughput for FRD, VRD, and ORD algorithms.

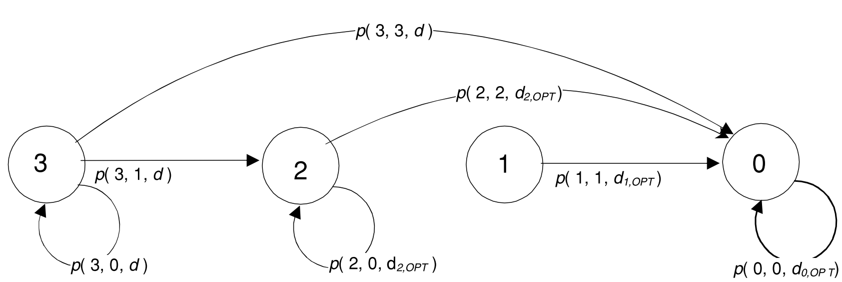

Fig. 7 State transition diagram for ORD to calculate $d_{3,OPT}$.

put, Fig. 9 illustrates that the slot throughput of ORD approaches 0.18 as the number of active stations increases, which is also the maximum throughput from pure ALOHA. That is, the proposed ORD algorithm can achieve near optimal slot throughput in resolving the contention of multiple active stations.

4. Implementation Issues

Notably, in previous simulation, the number of unranged active stations in each contention round is assumed to be known. However, only the number of collision clusters and the number of active stations that successfully transmitted their messages are known in real world. The number of initial active stations remains unknown because each collision clusters may consist of any number of messages transmitted by active stations. To effectively adopt the above random delay mechanisms, sensitivity analysis is first conducted and then schemes for estimating the number of active stations in each round are presented and investigated.

4.1 Sensitivity Analysis

To determine the influence of the error in estimating the number of active stations on average cycle time, sensitivity analysis is conducted for FRD and ORD algorithms and Figs. 10 and 11 display the results. In these figures, the notation "$err = k$" denotes the number of active stations with k units of estimation error, namely $k = \text{estimate}(i) - i$ where i and estimate(i) are the numbers of actual and estimated active stations, respectively. From these figures, it is observed that greater estimation error increases average cycle time and thus damages the throughput. In addition, negative estimation error increases average cycle time more than positive estimation error does. Therefore, if the number of active stations cannot be estimated accurately, the best strategy is to deliberately overestimate the number of active stations. Two estimation schemes

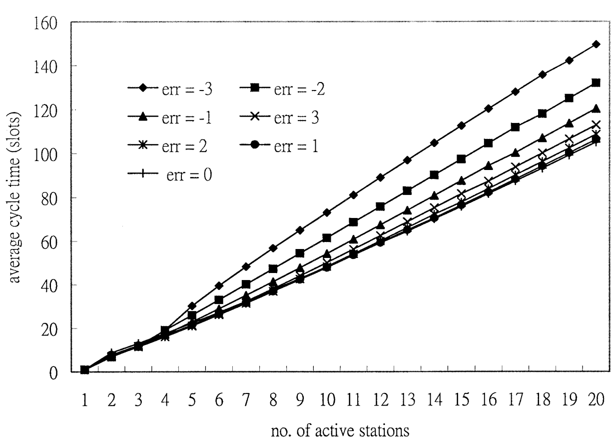

Fig. 10 Average cycle time of FRD with estimation errors.

are developed in the following subsection to enhance the throughput of the ranging process.

4.2 Maximum Likelihood Scheme

A maximum likelihood estimation scheme is developed herein based on the probability model. According to historical information regarding contention patterns, the most possible number of active stations in the next round is calculated. Let $p(i, j, k, d)$ denote the probability of that j out of i active stations successfully transmit their control messages and k collision clusters are observed, given that the random delay ranges between 0 and d. These $p(i, j, k, d)$'s are calculated by exhaustive simulation. Because the precise number of active stations i in the network can never be known, the number can be only estimated by observing the number of successfully transmitted active stations j and the number of collision clusters k. The historical information is the contention pattern of the previous contention round, and the window size is the number of previous contention rounds that need to be observed for estimating i of the next round. This scheme, with a window size of 2, works as follows:

1. In the first round of each cycle, if $j = j_0, k = k_0$ and $d = d_0$ are observed, take
$$i_{0,e} = arg_i \ \max\{p(i, j_0, k_0, d_0)\}$$
as the estimate of the number of active stations in the round. Then, $\max\{i_{0,e} - j_0, 2k_0\}$ can be taken as the estimate of active stations in the second round.
2. In the second round, if $j = j_1, k = k_1$ and $d = d_1$ are observed, take
$$i_{1,e} = arg_i \ \max\{p(i + j_0, j_0, k_0, d_0) * p(i, j_1, k_1, d_1)\}$$
as the estimate of the number of active stations in the round. Then, $\max\{i_{1,e} - j_1, 2k_1\}$ can be taken as the estimate of active stations in the third round.

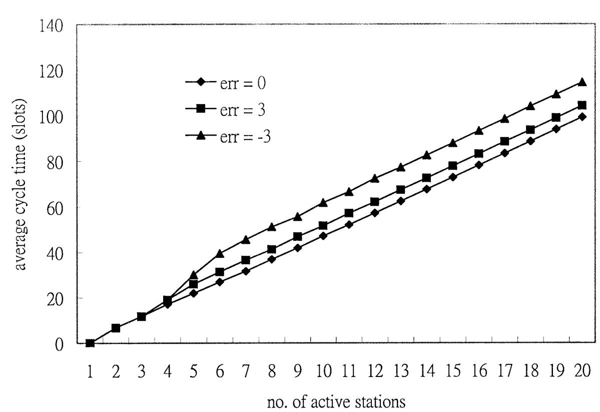

Fig. 11 Average cycle time of ORD with estimation errors.

3. Follow above procedures round by round until all active stations in the cycle are resolved.

4.3 Average Likelihood Scheme

Another estimation scheme is based on an average likelihood approach to estimate the number of active stations in the next round. Based upon the expectation approach, the expected value of i is used to estimate the number of active stations in the current round. The basic derivation of the average likelihood algorithm is the same as that of the maximum likelihood algorithm. This scheme is formally stated, with a window size of 2, as follows:

1. In the first round of each cycle, if $j = j_0, k = k_0$ and $d = d_0$ are observed, take
$$i_{0,e} = \left\lceil \sum_i (i * p(i, j_0, k_0, d_0)) \right\rceil$$
as the estimate of the number of active stations in the round. Then, $\max\{i_{0,e} - j_0, 2k_0\}$ can be taken as the estimate of active stations in the second round.
2. In the second round, if $j = j_1, k = k_1$ and $d = d_1$ are observed, take
$$i_{1,e} = \left\lceil \sum_i (i * p(i + j_0, j_0, k_0, d_0) * p(i, j_1, k_1, d_1)) \right\rceil$$
as the estimate of the number of active stations in the round. Then, $\max\{i_{1,e} - j_1, 2k_1\}$ can be taken as the estimate of active stations in the third round.
3. Follow above procedures round by round until all active stations in the cycle are resolved.

4.4 Effect Analysis for Estimation Schemes

For analytical and comparative purpose, the performance of the globally optimal random delay algorithm is combined with the maximum likelihood and average likelihood schemes with a window size of 2. Meanwhile, "initial$(i) = x$" denotes that the estimation number of active stations for the first round in contention cycle is equal to x given that the real number of active stations is i. From Fig. 12, the average likelihood scheme produces a slightly shorter cycle time than that of the maximum likelihood scheme. In Fig. 13, when $n \leq 10$, overestimation produces the same results as previously. However, underestimation does not significantly increase the average cycle time in either estimation scheme. This phenomenon occurs because the estimation schemes are based on historical information, not mere guesses, and thus they can rapidly accommodate themselves to the real situation. Consequently,

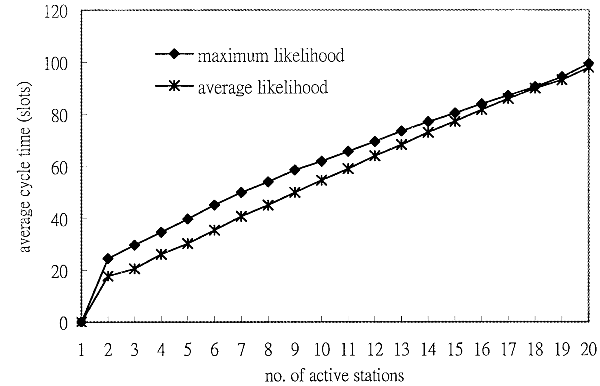

Fig. 12 Average cycle time for ORD with initial$(i) = i$.

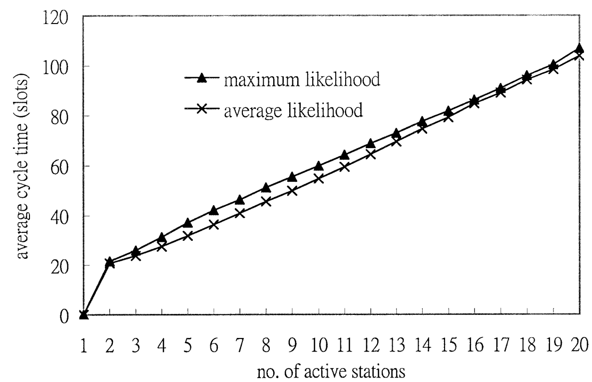

Fig. 13 Average cycle time for ORD with initial$(i) = 10$.

the novel estimation schemes presented herein can help ranging algorithms to enhance HFC network performance.

5. Conclusion

A ranging algorithm calculates the distance between the headend and the station for medium access control in HFC networks. The ranging processes for the DOCSIS standard is detailed herein. To enhance slot throughput, minimizing the ranging cycle time is essential. Therefore, a practical and efficient mean of resolving collisions is to randomly delay the transmission of ranging messages.

Three algorithms, FRD, VRD, and ORD, are developed to determine the optimal random delay for each contention round so as to minimize the average cycle time. The fundamental idea to the algorithms is to model the contention resolution process in a finite state machine in which the state transition probabilities are exhaustively calculated by simulation. The ORD is demonstrated via simulation to effectively minimize the contention cycle time and approach theoretically optimal throughput from pure ALOHA. For purposes of practicality in implementation, the sensitivity of the estimation error is assessed. Negative estimation error results in lower throughput than positive estimation error does. Consequently, if the number of active stations cannot be accurately estimated, it is preferably to overestimate the number of active stations than underestimate them. Additionally, based on the historical information about the pattern of the contention results, the maximum likelihood and average likelihood schemes are developed to estimate the number of active stations. The simulation indicates that the proposed estimation schemes are effective even when the estimate of the number of initially active stations is inaccurate. In summary, the proposed random delay mechanisms assisted with proposed estimation schemes can effectively help ranging algorithms to enhance HFC network performance.

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