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A multi-layer collision resolution multiple access protocol for wireless networks *

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In mobile communication networks operating in unreliable physical transmission, random access protocol with the collision resolution (CR) scheme is more attractive than the ALOHA family including carrier sense multiple access (CSMA) [IEEE Networks (September 1994) 50–64], due to likely failure on the channel sensing. Being a member of CR family schemes, a protocol known as *non-preemptive priority multiple access* (NPMA) is utilized in a new high-speed wireless local area network, HIPERLAN, standardized by European Telecommunication Standard Institute (ETSI). A conceptually three-layer CR multiple access protocol generalized from NPMA, supporting single type of traffic, is thus presented and analyzed in this paper. The CR capability of such a protocol (and hence NPMA) is proved to be significant by numerical substantiation that additional collision detection schemes are dispensable; also its throughput/delay performance is excellent when the proportion of the transmission phase to a channel access cycle is large enough (i.e., the winner of contention should transmit all of its packets successively). On the other hand, the simulated performance of NPMA serving integrated traffic is not fully satisfactory, primarily due to its distributed control mode and distinguishing traffic types only by the prioritization process.

1. Introduction

An efficient random access protocol design is essential in a wireless (mobile) network. Popular CSMA family protocols suffer from the difficulty of reliable channel sensing [3,11]. Collision resolution (CR) concept hence constructs another family of protocols more involving stability issue into concerns, such as alternative tree-algorithms [1,2], polling [18] or probing [10], and splitting algorithms [1,8,14]. These CR schemes alleviate the unstability problem by spreading the traffic into different subsets. New versions of this family protocols have been proposed, such as Group Randomly Addressed Polling (GRAP) [5], spatial-GRAP with reservation (SR-GRAP) [6], and the distributed queuing random access protocol (DQRAP) [19], etc. GRAP is an enhanced version of RAP [4], in which the grouping and random addressing conceptually construct two CR layers, and a product space of orthogonal signaling is applied [3]. It is a centralized/distributed system, since the groups are distributedly randomly chosen by each mobile node, and the transmission process is scheduled by the central processor. This hybrid control mode aggregates the simple and efficient operation of the distributed scheme, and the reliable communication under centralized control. SR-GRAP has been demonstrated efficient for upstream broadband communication over CATV networks for integrated CBR-VBR multimedia traffic, and its spatial grouping in long propagation delay actually provides another layer of collision resolution. DQRAP approaches the perfect scheduling system, the M/D/1 system, by both providing those collided nodes with a sequential CR process via minislots and the successfully accessed nodes with reserved data slots. In wireless communications, however, the required two global queues in DQRAP are difficult to maintain, since its distributed control actually depresses its performance as a result of the unreliable channel sensing.

What is indicated above is the prevalence of applications of “multi-layer CR” which take the advantage of the multiple effect of each CR layer without requiring much bandwidth (or time-slot overhead) expansion. European Telecommunication Standard Institute is standardizing a new high speed wireless local area network, HIPERLAN [7]. A protocol known as *non-preemptive priority multiple access* (NPMA) is utilized in this network as the channel access protocol. According to NPMA, there are two phases before the transmission in one channel access cycle: the prioritization phase and the contention phase. Through the prioritization phase, only those users (that have packets to send) with the highest priority in this channel access cycle can enter the contention phase. The contention phase combines an elimination scheme and a yield scheme, resolving the contending nodes with the same highest priority such that dominantly only one will survive. The survival(s) gets the right of transmission. We observed that this protocol similarly belongs to the CR family with the elimination and yield schemes as two CR layers. It also inspires us that if the priority can generally be viewed as an address being randomly defined, this multiple access protocol would consequently have three CR layers, with the first one mathematically equivalent to the orthogonal signaling of RAP protocol [4] but in the version of time-division [3]. This concept is applied in section 2, where the resultant three-layer collision resolution multiple access protocol is analyzed and simulated in section 3. In section 4, formal evaluation of NPMA

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supporting integrated services is performed by simulations. Finally, some concluding remarks are made in section 5.

2. Descriptions of the original and modified NPMA protocols

2.1. Original NPMA protocol

There are three phases fundamentally composing one channel access cycle (CAC) in NPMA protocol, which are prioritization phase, contention phase and transmission phase as illustrated in figure 1. Details of these phases are described as follows [7]:

1. *Prioritization phase.* Different priorities ranging from 0 to $m_{\mathrm{CAP}} - 1$ are applied to distinguish traffic types. Active users (users with packets ready to be transmitted) accommodating packets with their type of priority l listen for the duration of l *prioritization slot*s, and then transmit a burst for the duration of the *priority assertion interval*. The right of contention is bestowed to an active user if the channel is sensed idle before the bursting period of this user. Consequently, an active node holding packets with the highest priority gets the right of contention in current CAC. The duration of the prioritization slot and the priority assertion interval are i_{PS} and i_{PA}, respectively.
2. *Contention phase.* The contention phase consists of two parts, the elimination phase and then the yield phase. A contending node desires to eliminate others in the elimination phase. After then, a survivor of the elimination phase (i.e., a contending node which was not eliminated by other nodes in this phase) tries to yield the right of transmission to other survivors in the yield phase. These two phases in NPMA protocol are designed as the time-division CR scheme. In the elimination phase, a contending node transmits a burst to eliminate other contending nodes, and then listens to the channel for the duration of the *elimination survival verification interval*, i_{ESV}. A contending node survives the elimination phase and enters the yield phase if and only if it senses the channel idle during its elimination survival verification interval. The duration of the bursting is bounded inclusively between 0 and m_{ES} *elimination bursting slot*s, with a memoryless contention scheme that the probability of bursting in an elimination slot interval is P_{E}. The duration of the elimination slot is i_{ES}. In the yield phase, a contending node (a survivor of the elimination phase) listens for a duration between 0 and m_{YS} *yield slot*s, and it survives if and only if it senses the channel idle during its yield listening. Its contention mechanism is also memoryless with the probability of yield listening in a yield slot interval being P_{Y}. The duration of the yield slot is i_{YS}.
3. *Transmission phase.* Survival(s) of the yield phase enters the transmission phase and transmits its packets.

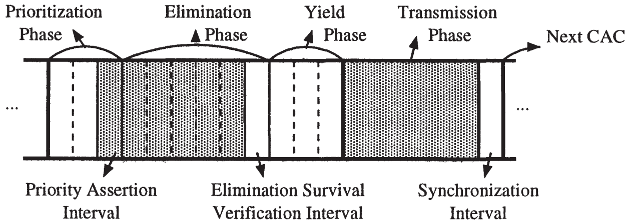

Figure 1. Timing diagram of one CAC.

At the end of a CAC, a *synchronization interval* with duration i_{CS} is provided for each active node to achieve the synchronization with others. The timing diagram of a CAC shown in figure 1 illustrates an instance that the most prioritized packets ready to be sent in this CAC belong to the traffic type of priority 2. Among all active users possessing packets of this priority level, some may choose 5 elimination slots for bursting while the others choose less. The former are thus permitted to enter the yield phase. Some (one) of these survivals listen for the channel for 3 slots and then start transmitting packets while the others listen for longer and yield the right of transmission. If more than two active users are granted for transmission, the length of the transmission phase can be decided just by the longer (longest) transmission period, or some process similar to "collision detection" could be adopted to constraint the length of a collided transmission. For example, those granted nodes may stop transmission without receiving positive acknowledgment corresponding to foregone packets during some specific duration. The synchronization interval then begins as the channel is sensed quiet. In figure 1, the shadowed region represents bursting or transmitting while the blank one represents listening. Beside fixed durations (such as priority assertion interval, elimination survival verification interval and synchronization interval), the overall length of the CAC obviously depends on the highest priority of active users, the maximum and minimum numbers of the elimination and yield slots chosen by contending users respectively, and the length of transmission. It is hence variable for each CAC.

Illustrated above is the NPMA protocol operating under the condition of "channel access with synchronization", that is, when a channel access is desired to be commenced as the channel is not considered free. If the channel has been observed to be idle for longer than a specific period, the channel is considered to be free, and the transmission phase may take place immediately without the prioritization and contention phases. Consequently, NPMA operation under light load should approximate CSMA [16] with an additional synchronization interval. To be more precise, the NPMA scheme despite of the prioritization process works similarly to non-persistent CSMA as follows. In non-persistent CSMA, a new arrival during the transmission period is backlogged and it will be transmitted with probability q similar to other backlogs. Corresponding to NPMA, this probability q turns to be a function of the global decision of each contending user about the numbers of elimination and yield slots. However, it is apparent that NPMA belongs to the CR family, actually with two CR layers: elimination and yield phases. Both of these layers apply time-division in decentralized form to resolve (avoid) possible collisions for improving the probability of successful transmission, based on which these two mechanisms are equivalent, e.g., two consecutive yield phases or elimination phases can compose the contention phase producing the same mathematical structure. The above observation about the relationship of NPMA, non-persistent CSMA and multi-layer CR schemes may also imply some mathematical equivalency between CSMA and CR family mechanisms.

To further investigate CR characteristics of the prioritization phase of NPMA protocol, we modified it as a three-layer CR random access protocol, which explores the CR capability of such a distributed control scheme.

2.2. Modified NPMA protocol – A three-layer CR protocol

The three-layer CR protocol studied here results from NPMA scheme in which the priority is generalized to be randomly defined, transforming the prioritization phase into the *randomly addressing phase*. This term “random address” originates from the RAP family protocols [4,5] which can be implemented by orthogonal signals or in the time-slot map [3]. Actually the prioritization phase in NPMA protocol may also be interpreted as a CR layer applying fixed assignment according to the traffic type, while in the three-layer CR protocol, this corresponding randomly addressing phase applies stochastic assignment supporting single traffic type. The operation of the randomly addressing phase is elaborated as follows:

- *Randomly addressing phase.* The applied random addresses from 0 to $m_{\mathrm{CAP}} - 1$ are distinguished by different numbers of *addressing slot*s, i.e., users choosing random address l listen for the duration of l addressing slots, and then transmit a burst for the duration of the *assertion interval* and get the right of contention if the channel is sensed idle. An active node is thus licensed for contention if it has chosen the smallest number as its address in this CAC. The duration of the addressing slot and the assertion slot are i_{PS} and i_{PA}, respectively.

The elimination and yield phases as the second and third CR layers operate as in original NPMA protocol. The additional CR layer, randomly addressing phase, provides more resolution capability to yield a more efficient random access.

3. Analysis of the three-layer CR protocol

In this section the modified NPMA scheme as a three-layer CR protocol is analyzed substantially with simulated results. Since only single traffic type is afforded, the data traffic is assumed in our analysis.

3.1. Assumptions

To simplify the analysis of this multi-layer CR protocol, without loss of generality, we assume:

1. Each mobile node generates new packets according to Poisson distribution with the same arrival rate λ.
2. The random address can be uniformly chosen.
3. Totally N nodes are under the coverage area being analyzed, and each node has one buffer.
4. The transmission phase may be shorter when a collision occurs, i.e., a collision detection scheme in the transmission phase is allowed.
5. Once an active node successfully accesses the channel and begins to transmit its packet, it may simultaneously generate a new packet that will join the randomly addressing phase or maybe even the contention of the succeeding CAC.

3.2. Throughput analysis

Considering the above assumptions, we can model the proposed protocol as a one-dimensional Markov chain. Each state of this Markov chain represents the number of active nodes under the coverage area *at the beginning of each CAC*. The number of new active arrivals during a certain CAC is a Binomial distribution with parameters $N-k+1$ and $1-\mathrm{e}^{-\lambda T}$ if it contains a successful transmission or $N-k$ and $1-\mathrm{e}^{-\lambda T}$ if it contains a collision, where k is the number of active users at the beginning of this CAC with duration T. Corresponding to the current number of active nodes, we can compute the probability associated with the number of nodes selecting the same number as the smallest address in this CAC. These active nodes actually join the contention, and given how many they are, the probability that only one of them accesses the channel can also be derived. The transition probability from state i to state j is hence

$$
\begin{aligned}
&P_{\mathrm{tran}}(i,j)\\
&\quad= \begin{cases}
\dbinom{N}{j}\bigl(1-\mathrm{e}^{-\lambda T(0)}\bigr)^{j}\mathrm{e}^{-\lambda T(0)(N-j)}, \\
\quad i=0,\ 0\leqslant j\leqslant N, \\
\displaystyle\sum_{k=1}^{i}\sum_{l=0}^{m_{\mathrm{CAP}}-1}\widehat{P}_i(k,l)P_{\mathrm{succ}}^{(k)}\mathrm{e}^{-\lambda(\tau(l)+T_{\mathrm{succ}}(k))(N-i+1)}, \\
\quad 1\leqslant i\leqslant N,\ j=i-1, \\
\displaystyle\sum_{k=1}^{i}\sum_{l=0}^{m_{\mathrm{CAP}}-1}\widehat{P}_i(k,l)\bigl[P_{\mathrm{succ}}^{(k)}\phi_{\mathrm{succ}}^{(k,l)}(N-i+1,j-i+1) \\
\quad +\bigl(1-P_{\mathrm{succ}}^{(k)}\bigr)\phi_{\mathrm{coll}}^{(k,l)}(N-i,j-i)\bigr], \\
\quad 1\leqslant i< N,\ j\geqslant i, \\
\displaystyle\sum_{k=1}^{i}\sum_{l=0}^{m_{\mathrm{CAP}}-1}\widehat{P}_N(k,l)\bigl[P_{\mathrm{succ}}^{(k)}\bigl(1-\mathrm{e}^{-\lambda(\tau(l)+T_{\mathrm{succ}}(k))}\bigr) \\
\quad +\bigl(1-P_{\mathrm{succ}}^{(k)}\bigr)\bigr],\quad i=j=N
\end{cases}
\end{aligned}
\tag{1}
$$

with

$$\phi_{\text{type}}^{(k,l)}(m,n) = \binom{m}{n}\left(1 - \mathrm{e}^{-\lambda(\tau(l)+T_{\text{type}}(k))}\right)^{n} \times \mathrm{e}^{-\lambda(\tau(l)+T_{\text{type}}(k))(m-n)}, \tag{2}$$

where $\widehat{P}_i(k,l)$, $1 \leqslant k \leqslant i$, $0 \leqslant l \leqslant m_{\text{CAP}} - 1$, is the probability that there are k active nodes having the smallest random number l in a certain CAC, given totally i active nodes. $P_{\text{succ}}^{(k)}$ is the probability that only one active node accesses the channel given k contending nodes. $\tau(l)$ is the interval of the randomly addressing phase in one CAC given the smallest random address l. $T_{\text{succ}}(k)$, $T_{\text{coll}}(k)$ and $T(k)$ all represent the average total length of the contention phase, the transmission phase, and the synchronization interval given k contending nodes, with $T_{\text{succ}}(k)$ given a successful transmission, and $T_{\text{coll}}(k)$ given a collision in a certain CAC. Therefore,

$$\begin{aligned}
&\widehat{P}_i(k,l) = \binom{i}{k}\left(\frac{1}{m_{\text{CAP}}}\right)^{k}\left(1 - \frac{l+1}{m_{\text{CAP}}}\right)^{i-k},\\
&\tau(l) = l \cdot i_{\text{PS}} + i_{\text{PA}},\\
&\quad 0 \leqslant l \leqslant m_{\text{CAP}} - 1.
\end{aligned} \tag{3}$$

To get $P_{\text{succ}}^{(k)}$, $T_{\text{succ}}(k)$, $T_{\text{coll}}(k)$ and $T(k)$, we first derive the probability of n survivals transmitting bursts for m slots given k contending nodes of the elimination phase, $P_{\text{ES}}^{(k,n,m)}$, and the probability of n survivals listening for m slots given k contending nodes of the yield phase, $P_{\text{YS}}^{(k,n,m)}$. It is a straightforward derivation from the system parameters that

$$\begin{aligned}
P_{\text{ES}}^{(k,n,m)} &= \begin{cases}
\binom{k}{n}\left[P_{\text{E}}^{m}(1-P_{\text{E}})\right]^{n}\left(1-P_{\text{E}}^{m}\right)^{k-n},\\
\quad 0 \leqslant m < m_{\text{ES}},\\
\binom{k}{n}P_{\text{E}}^{m_{\text{ES}}n}\left(1-P_{\text{E}}^{m_{\text{ES}}}\right)^{k-n},\\
\quad m = m_{\text{ES}},
\end{cases}\\
P_{\text{YS}}^{(k,n,m)} &= \begin{cases}
\binom{k}{n}\left[P_{\text{Y}}^{m}(1-P_{\text{Y}})\right]^{n}P_{\text{Y}}^{(m+1)(k-n)},\\
\quad 0 \leqslant m < m_{\text{YS}},\\
P_{Y}^{m_{\text{YS}}n}\delta(n-k),\\
\quad m = m_{\text{YS}},
\end{cases}
\end{aligned} \tag{4}$$

where we define $0^0 = 1$ and $0^i = 0$ for $i > 0$. Using $P_{\text{ES}}^{(k,n,m)}$ and $P_{\text{YS}}^{(k,n,m)}$, we can see that

$$P_{\text{succ}}^{(k)} = \sum_{n=1}^{k}\left(\sum_{m=0}^{m_{\text{ES}}}P_{\text{ES}}^{(k,n,m)}\right)\left(\sum_{m=0}^{m_{\text{YS}}}P_{\text{YS}}^{(n,1,m)}\right). \tag{5}$$

As a result, the probability that the elimination phase has n slots and the yield phase has m slots given k contending nodes, $P_{\text{EY}}^{(k,n,m)}$, is

$$P_{\text{EY}}^{(k,n,m)} = \sum_{i=1}^{k}\left[P_{\text{ES}}^{(k,i,n)}\sum_{j=1}^{i}P_{\text{YS}}^{(i,j,m)}\right], \tag{6}$$

$$1 \leqslant k \leqslant N,\ 0 \leqslant n \leqslant m_{\text{ES}},\ 0 \leqslant m \leqslant m_{\text{YS}}.$$

If a successful (collided) transmission is also given, the above probability is modified as $P_{\text{EY,succ}}^{(k,n,m)}$ ($P_{\text{EY,coll}}^{(k,n,m)}$), and

$$\begin{aligned}
P_{\text{EY,succ}}^{(k,n,m)} &= \frac{\sum_{i=1}^{k}[P_{\text{ES}}^{(k,i,n)}P_{\text{YS}}^{(i,1,m)}]}{\sum_{n}\sum_{m}P_{\text{EY,succ}}^{(k,n,m)}},\\
P_{\text{EY,coll}}^{(k,n,m)} &= \frac{\sum_{i=2}^{k}\left[P_{\text{ES}}^{(k,i,n)}\sum_{j=2}^{i}P_{\text{YS}}^{(i,j,m)}\right]}{\sum_{n}\sum_{m}P_{\text{EY,coll}}^{(k,n,m)}},
\end{aligned} \tag{7}$$

$$1 \leqslant k \leqslant N,\ 0 \leqslant n \leqslant m_{\text{ES}},\ 0 \leqslant m \leqslant m_{\text{YS}}.$$

Therefore,

$$\begin{aligned}
T(k) &= \sum_{n=0}^{m_{\text{ES}}}\sum_{m=0}^{m_{\text{YS}}}\left[P_{\text{EY}}^{(k,n,m)}(ni_{\text{ES}} + mi_{\text{YS}})\right] + i_{\text{ESV}}\\
&\quad + \left[P_{\text{succ}}(k)T_{\text{s}} + (1 - P_{\text{succ}}(k))T_{\text{c}}\right]\\
&\quad + i_{\text{CS}}, \quad 1 \leqslant k \leqslant N,\\
T_{\text{succ}}(k) &= \sum_{n=0}^{m_{\text{ES}}}\sum_{m=0}^{m_{\text{YS}}}\left[P_{\text{EY,succ}}^{(k,n,m)}(ni_{\text{ES}} + mi_{\text{YS}})\right]\\
&\quad + i_{\text{ESV}} + T_{\text{s}} + i_{\text{CS}}, \quad 1 \leqslant k \leqslant N,\\
T_{\text{coll}}(k) &= \sum_{n=0}^{m_{\text{ES}}}\sum_{m=0}^{m_{\text{YS}}}\left[P_{\text{EY,coll}}^{(k,n,m)}(ni_{\text{ES}} + mi_{\text{YS}})\right]\\
&\quad + i_{\text{ESV}} + T_{\text{c}} + i_{\text{CS}}, \quad 2 \leqslant k \leqslant N,
\end{aligned} \tag{8}$$

where T_{s} is the constant length of one packet, and T_{c} is the actual length of the transmission interval when a collision occurs. If there is no collision detection in the transmission phase, $T_{\text{c}} = T_{\text{s}}$.

Knowing the transition probabilities of this Markov chain, the steady state probabilities of i active nodes at the beginning of a CAC, $P_{\text{CAC}}(i)$, could be figured out. The average utility in one CAC $\overline{U}$, the average length of one CAC $\overline{T}$, and the throughput of the proposed scheme are

$$\begin{aligned}
\overline{U} &= \sum_{i=1}^{N}P_{\text{CAC}}(i)\left[\sum_{k=1}^{i}\sum_{l=0}^{m_{\text{CAP}}-1}\widehat{P}_i(k,l)P_{\text{succ}}(k)\right]T_{\text{s}},\\
\overline{T} &= P_{\text{CAC}}(0)(m_{\text{CAP}}i_{\text{PS}} + i_{\text{CS}})\\
&\quad + \sum_{i=1}^{N}P_{\text{CAC}}(i)\left[\sum_{k=1}^{i}\sum_{l=0}^{m_{\text{CAP}}-1}\widehat{P}_i(k,l)\bigl(\tau(l) + T(k)\bigr)\right],\\
\text{Throughput} &= \overline{U}/\overline{T}.
\end{aligned} \tag{9}$$

3.3. Delay analysis

Please recall that the Markov chain model to analyze the throughput is embedded at the beginning of each CAC.

However, while computing the waiting time of an active node, we have to know the exact timing when it becomes active. Hence the proposed model here is a *continuous time Markov process* with each state representing the number of active nodes under the coverage area. This model approximates the departure process as exponentially distributed. The transition rate from state i to state j is

$$Q(i,j) = \begin{cases} (N-i)\lambda, & 0 \leqslant i < N,\ j = i+1, \\ \mu(i), & 0 < i \leqslant N,\ j = i-1, \\ 0, & 0 \leqslant i \leqslant N,\ j \neq i-1,\ i, i+1, \\ -\sum_{k \neq i} Q(i,k), & 0 \leqslant i \leqslant N,\ j = i, \end{cases} \tag{10}$$

where

$$\begin{aligned} \mu(i) &= \sum_{k=1}^{i} \sum_{l=0}^{m_{\text{CAP}}-1} \widehat{P}_i(k,l) T_{\text{d}}^{-1}(k,l), \\ T_{\text{d}}(k,l) &= \left(P_{\text{succ}}^{-1}(k) - 1\right)\left(\tau(l) + T_{\text{coll}}(k)\right) \\ &\quad + \tau(l) + T_{\text{succ}}(k) \end{aligned} \tag{11}$$

are the departure rate given i active nodes and the average departure time given k contending nodes with the random address l, respectively. The precision of this approximation can be approved by the numerical results depicted later.

Now we can calculate the steady state probability of i active nodes under the coverage area at a random time, $\pi(i)$. Approximations of the average number of active nodes at a random time and the average arrival rate are respectively

$$\begin{aligned} \overline{N} &= \sum_{i=1}^{N} i\pi(i), \\ \overline{\lambda} &= \sum_{i=0}^{N} \left[(N-i)\lambda \cdot \pi(i)\right]. \end{aligned} \tag{12}$$

According to the well-known Little's formula [12], if all the arrivals leave the system eventually, then the average number of customers in the system equals to the average number of arrivals per unit of time multiplying the average responding time of a customer. Numerical values of system parameters applied in our system, following NPMA draft standard, are designed to provide high probability of successful transmission (high capability of collision resolution) over a wide range of the number of active users (which is of our interest). Together with our finite population model with each user possessing one buffer, this yields a finite average CR period and assures that all the arrivals leave the system eventually. Applying Little's formula, the average responding time of an active node is

$$\overline{T}_{\text{response}} = \frac{\overline{N}}{\overline{\lambda}}. \tag{13}$$

And the average delay, i.e., the average waiting time of an active node, is

$$\overline{D} = \overline{T}_{\text{response}} - T_{\text{s}} - i_{\text{CS}} \tag{14}$$

as an approximation.

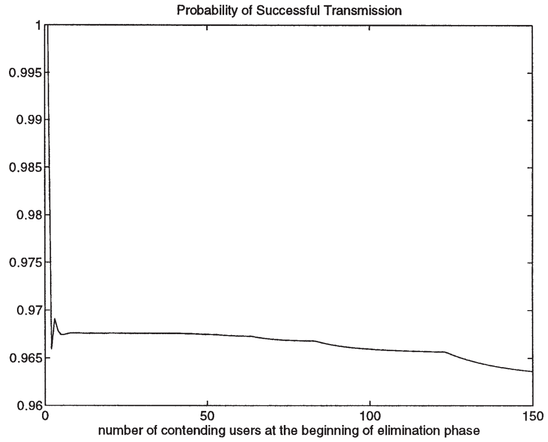

Figure 2. Probability of successful transmission.

Table 1
Numerical values of system parameters.

Parameter	i_{PS}	i_{PA}	i_{ES}	i_{ESV}	i_{YS}	i_{CS}
Value (normalized)	2.56e−5	2.56e−5	2.56e−5	2.56e−5	0.64e−5	2.56e−5
Parameter	m_{CAP}	m_{ES}	m_{YS}	p_{E}	p_{Y}	
Value	5	12	14	0.5	0.9	

3.4. Numerical results

The numerical system parameters are listed in table 1 according to [7]. Normalized values correspond to the transmission rate of the system. As a modified version, these parameters may be optimally determined yielding best performance with the stability into concern. We shall distinguish the attribution of the proposed protocol as a member of CR family in this paper. Following the assumptions 1–4 in section 3.1, numerical results are depicted in figures 2–7. Figure 2 demonstrates the probability of successful transmission as a function of the number of contending users at the beginning of the elimination phase. In throughput/delay performance, the analytical and the simulated results coincide closely shown in figure 3 (95% confidence interval is also shown), which also suggests the precision of the approximation in delay analysis. Figure 4 demonstrates the effect of the number of random addresses, where $m_{\text{CAP}} = 1$ represents the extinction of the first CR layer. Applying $m_{\text{CAP}} = 5$, comparisons of the performance with different numbers of users, different lengths of packets, and with/without a collision detection scheme in the transmission phase are shown in figures 5–7.

From those figures, we can observe that additional CR layer(s) is generally more desirable. It is not only because it improves the performance, but also applying more layers can lower the required resolution degree (and thus bandwidth) of each layer. In our case, m_{ES} and m_{YS} are both large enough (comparing to the number of users as illustrated in figure 2) that the variation of m_{CAP} results in little distinctness. On the contrary, due to the long overhead required by the CR scheme under decentralized control, the length of packets (or the transmission phase generally)

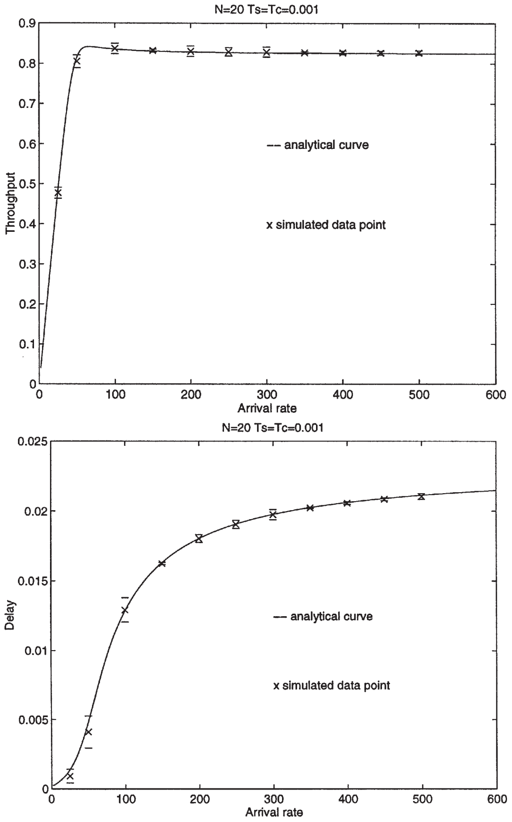

Figure 3. Coincidence of analytical and simulated data.

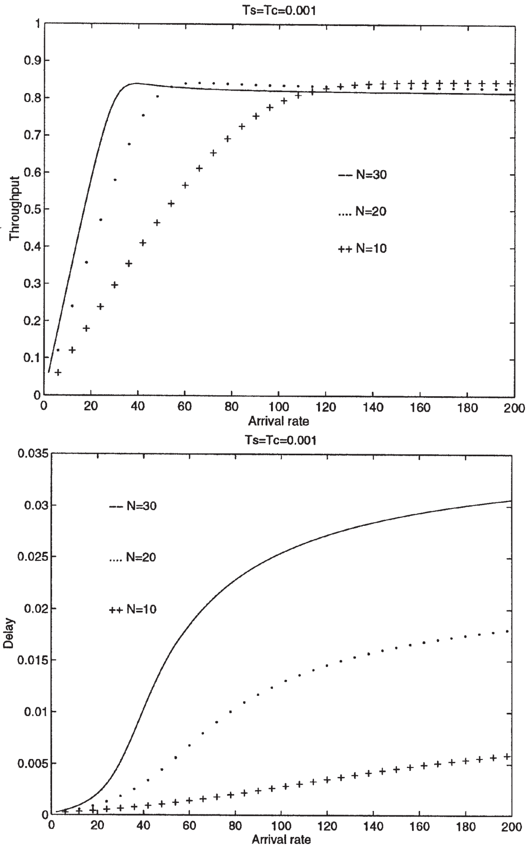

Figure 5. Performance comparison with different number of users.

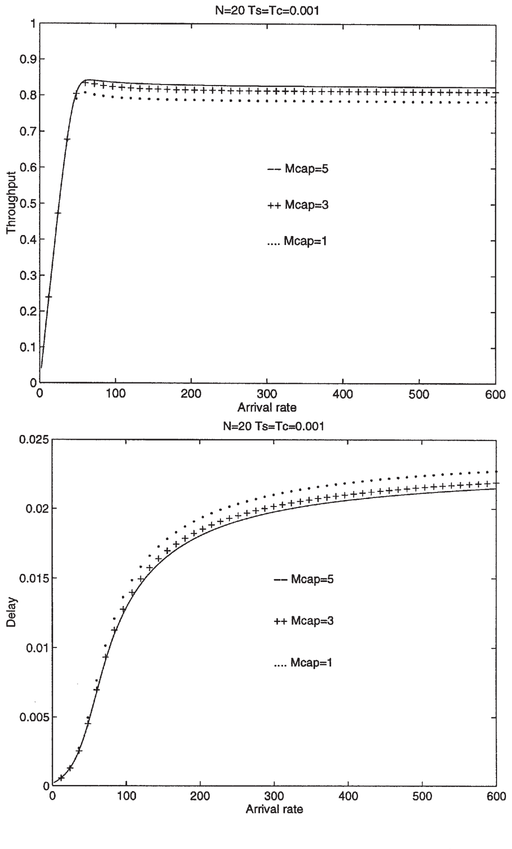

Figure 4. Effect of Mcap (the degree of resolution of the first CR layer).

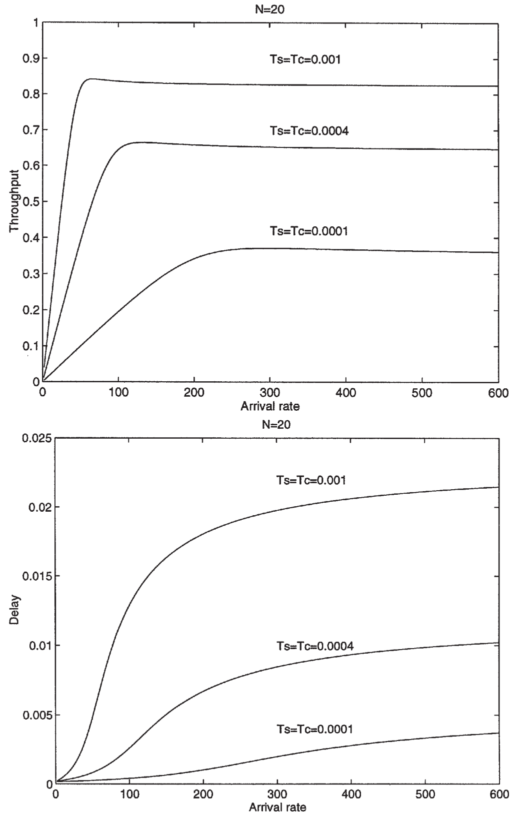

Figure 6. Performance comparison with different lengths of the transmission phase.

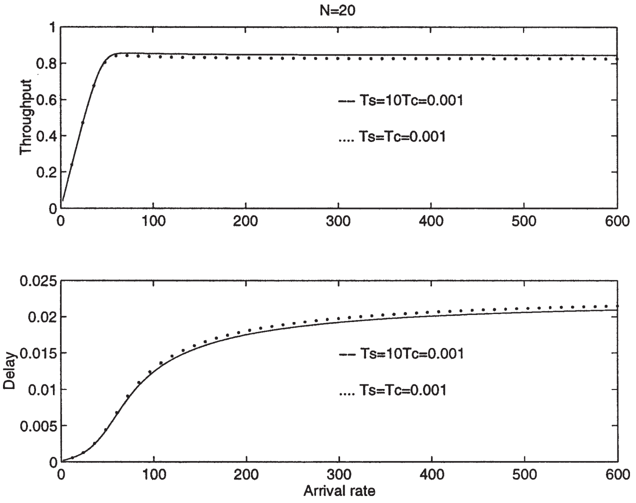

Figure 7. Effect of the collision detection scheme.

provides a tradeoff between the throughput and the delay. The throughput peak is approximately the proportion of the transmission phase to the average length of a CAC, and its variation depending on the length of the transmission phase is inversely proportional to that of the delay peak. As a result of the high successful resolution capability, the throughput curves under all conditions are flat enough once they reach the peak value, and the effect of an additional collision detection scheme in the transmission phase is not evident. This feasible CR process also leads to the excellent throughput/delay of this multi-layer CR protocol shown in figure 7 even as the number of users increases, as long as the proportion of the transmission phase to one CAC is large enough. Please recall that the unbacklogged model is applied in our analysis, i.e., each user has only one buffer. Consequently, the throughput/delay curves keep the value as the arrival rate is high enough to make the channel fully utilized by all users.

4. Simulations of original NPMA protocol for integrated service traffic

We have analyzed the performance of the modified version of NPMA protocol, which has transformed the prioritization phase into randomly addressing phase and hence capable of supporting traffic of a single type (data traffic in our analysis). In this section, the prioritization phase in NPMA protocol is considered to enable this protocol to operate over integrated traffic, including video, voice and data. We accommodate the following traffic models in our simulations:

1. *Video service.* A constant-bit-rate (CBR) video source is considered in this research. Since the transmission rate of HIPERLAN is up to 23 Mbps, we temporarily assume the video source with 1.5 Mbps as MPEG I type. Very-low-bit-rate video source as MPEG IV type dedicated to mobile radio channel, though not adopted in simulations, is included in our discussions.

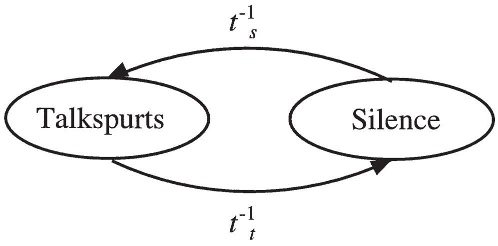

Figure 8. Speech model of talkspurts/silence.

2. *Voice service.* Figure 8 illustrates the transition diagram of the talkspurts and silence states as a two-state Markov chain. It is an on–off model that each voice source generates packets at constant bit rate in the talkspurts, and nothing as in silence state. Transition rates as shown are t_{s}^{-1} and t_{t}^{-1}, where t_{s} and t_{t} are the means of exponentially distributed sojourn periods in silence and talkspurts, respectively. Interarrival time of voice packets in talkspurts, similar to that of video packets, is the production of one-bit period and the number of bits of a packet.
3. *Data service.* Poisson distribution with rate λ is assumed to describe the data arrival process.

This original NPMA scheme has two formal CR layers, elimination and yield phases. Please recall that the throughput/delay performance of modified NPMA protocol is dominated by the length of transmission phase in one CAC. Transmitting successive packets in this phase, as the store-and-forward scheme, is thus more reasonable than the single-hop one (i.e., transmitting one packet in one CAC). The following rules are not defined in [7] but assumed in our simulation process:

1. *Prioritization.* The priority is granted according to different quality-of-service (QoS) requirements. Considering delay and drop-rate constraints, we label the video, voice and data traffics with priority 0, 1, 2, respectively; i.e., $m_{\mathrm{CAP}} = 3$.
2. *Permission of contention.* According to the priority level, video packets can join the contention of current CAC as long as they are generated in the last one. However, this causes rapidly saturation of the channel by video transmissions due to high video source rate relative to other traffics. Less prioritized services would therefore be blocked or compelled by unacceptable long delay even with only a few active video users. We thus assume that an active video user could join the contention process if and only if it has more than B packets in its buffer, where $B > 1$ is a parameter in our simulation. Voice and data services would not be applied the same compulsion for the maximum-delay consideration, as they have already been less prioritized. This requirement for the permission of contention can also improve the throughput/delay performance of the overall operation, not only by allocating more resource for voice and data services, but also by increasing the proportion of the video transmission phase in one CAC.

An ideal error-free channel is initially considered for the simulation, followed by a practical situation with some moderate bit-error rate in transmission due to random noise on the radio channel. Acknowledgment procedures, however, are assumed in both cases to be ideally away from the channel noise and multi-user interference. Propagation delay between the transmitter and corresponding receiver (e.g., a base station if there is one) is also assumed to be smaller than a packet transmission time. The length of the transmission phase is equivalent to the transmission time of total packets held by the user who has successfully accessed the channel. When a collision occurs, this length is the same as the transmission time of one packet if each active user who has accessed the CAC has one packet to send, and twice if one of these active users has more than one packet in its buffer. This is a consequence of the assumption that before transmitting out the second packets, the transmitter would receive negative acknowledgment (or not receive positive acknowledgment) corresponding to the unsuccessful transmission of the first packet, and hence close the transmission phase. Here we are interested in the case of more voice users and trying to find their appropriate operating range indicated by their required drop rate given some fixed numbers of active video and data users. Furthermore, jitter distributions of video and voice traffic are examined to explore the capability of HIPERLAN in providing real-time multimedia services. We define the “maximum jitter” as the maximum time separation between the waiting times of successively transmitted packets, and the “mean jitter” as the average of these time separations. These two parameters, together with its second moment, also characterize the synchronization skew between related media originated from the same source through different services, e.g., video and voice in video conferencing.

Each case of distinct conditions in our simulations runs 50 times to take the ensemble average, during each time of which it runs for a 100-seconds-channel-time period.

Case 1. Error-free communication

The decentralized access scheme of NPMA makes it blind to the violation of some active users in the contention procedure to gain more channel resource. This violation is attractive to less-prioritized users because they can never access the channel as long as those with higher priority are active. We thus consider such case that some data users pretend to process the highest priority and contend with video users in our simulations. Such influence to voice users is for investigating the integrity and ability of coexisting with other random access protocols of NPMA scheme.

System and source parameters applied in this part of simulations are listed in table 2, together with those parameters set in table 1. We consider at most 4 video users simultaneously turning active, in which case less than 40% of the channel resource is allocated to voice and data traffic. Some of the numerical values of source parameters can be referred to [9,13]. The endurable probability of loss of video and voice packets are 0.001 and 0.01, respectively. Table 3 shows the notations of all performance indices.

Table 2
Numerical values of system and source parameters.

Notation	Description	Numerical value
R_{c}	channel transmission rate	10 Mbps
fake_no	number of data users breaking the operation rule	variable
T	number of bits in one packet	1000
B	least number of packets in the buffer required for video users to join contention	10 or 20
N_{ve}	number of video users	0 or 4
N_{v}	number of voice users	variable
N_{d}	number of data users	35
R_{ve}	video source rate	1.5 Mbps
$D_{\mathrm{max\_ve}}$	maximum delay of video packets	250 ms
R_{v}	voice source rate	32 Kbps
t_{s}	mean sojourn period in silence state	1.35 s
t_{t}	mean sojourn period in talkspurts state	1.0 s
$D_{\mathrm{max\_v}}$	maximum delay of voice packets	32 ms
λ	average data arrival rate	5 packets/s

Table 3
Notations of performance indices.

Performance index	Notation
Video packet drop rate	DR_{ve}
Voice packet drop rate	DR_{v}
Throughput	η
Delay of video (ms)	D_{ve}
Delay of voice (ms)	D_{v}
Delay of data (ms)	D_{d}
Max jitter of video packets (ms)	$J_{\mathrm{ve}}^{\max}$
Mean jitter of video packets (ms)	$\overline{J_{\mathrm{ve}}}$
2nd moment of jitter of video packets (μs)	$\tilde{J}_{\mathrm{ve}}$
Max jitter of voice packets (ms)	$J_{\mathrm{v}}^{\max}$
Mean jitter of voice packets (ms)	$\overline{J_{\mathrm{v}}}$
2nd moment of jitter of voice packets (μs)	$\tilde{J}_{\mathrm{v}}$

Tables 5–10 demonstrate the case with four video users, and table 11 is that with voice and data users only. Comparisons between tables 5–7 and 8–10 reveal the effect of the parameter B, the least number of packets in the buffer required for video users to join contention. The associated observations when B gets larger are discussed and listed as follows:

- More voice users are allowed to be served yielding higher throughput, while the delay of video packets also increases as expected.
- As a result of that more bandwidth is granted to voice and data services, the corresponding delay performance is improved, especially that of the latter. However, the extreme decrease of the delay of data traffic extenuates when *fake_no*, the number of data users breaking the operation rule, increases.
- Jitter distribution for video service is more widespread, but that for voice is more centralized. This is reasonable together with the above two statements which indicate the improvement in the channel resource rearrangement.

Table 4
Numerical values of parameters different from those applied in case 1.

Notation	Description	Numerical value
bit_err_rate	bit-error rate in transmission	10^{-6}
B	as in table 2	20 or 40
T	number of bits in a packet	500

Table 5
Case 1: $N_{\rm ve} = 4,\ N_{\rm d} = 35,\ B = 20,\ fake\_no = 0.$

$N_{\rm v}$	50	52	54	56	58	60
$DR_{\rm v}$	6.577e−4	1.202e−3	2.032e−3	3.823e−3	6.603e−3	1.111e−2
η	0.6855	0.6883	0.6908	0.6933	0.6960	0.6984
$D_{\rm ve}$	6.933	6.938	6.943	6.950	6.958	6.967
$D_{\rm v}$	11.09	11.57	12.02	12.48	12.98	13.45
$D_{\rm d}$	18.35	25.57	38.59	58.97	93.28	148.6
$J_{\rm ve}^{\rm max}$	20.94	20.98	20.97	21.00	21.01	21.08
$\overline{J_{\rm ve}}$	1.270	1.270	1.270	1.270	1.270	1.270
$\tilde{J}_{\rm ve}$	8.89043	8.89057	8.89086	8.89138	8.89205	8.89331
$J_{\rm v}^{\rm max}$	30.88	31.27	31.30	31.50	31.59	31.65
$\overline{J_{\rm v}}$	1.786	1.792	1.799	1.806	1.814	1.821
$\tilde{J}_{\rm v}$	19.6384	20.4423	21.2362	22.0451	22.9199	23.7706

Table 6
Case 1: $N_{\rm ve} = 4,\ N_{\rm d} = 35,\ B = 20,\ fake\_no = 10.$

$N_{\rm v}$	50	52	54	56	58	60
$DR_{\rm v}$	1.076e−3	2.120e−3	4.120e−3	6.615e−3	1.070e−2	1.712e−2
η	0.6855	0.6882	0.6907	0.6932	0.6956	0.6979
$D_{\rm ve}$	6.932	6.937	6.942	6.948	6.953	6.960
$D_{\rm v}$	11.43	11.92	12.34	12.84	13.30	13.75
$D_{\rm d}$	12.26	17.97	27.45	40.28	62.29	97.28
$J_{\rm ve}^{\rm max}$	21.01	21.02	21.04	21.06	21.08	21.12
$\overline{J_{\rm ve}}$	1.270	1.270	1.270	1.270	1.270	1.270
$\tilde{J}_{\rm ve}$	8.89072	8.89087	8.89117	8.89152	8.89216	8.89402
$J_{\rm v}^{\rm max}$	31.23	31.35	31.43	31.54	31.64	31.71
$\overline{J_{\rm v}}$	1.844	1.855	1.864	1.873	1.884	1.893
$\tilde{J}_{\rm v}$	20.9834	21.9116	22.7828	23.6693	24.5762	25.449

Table 7
Case 1: $N_{\rm ve} = 4,\ N_{\rm d} = 35,\ B = 20,\ fake\_no = 20.$

$N_{\rm v}$	48	50	52	54	56	58
$DR_{\rm v}$	1.219e−3	2.326e−3	4.579e−3	6.929e−3	1.140e−2	1.713e−2
η	0.6828	0.6854	0.6880	0.6905	0.6930	0.6951
$D_{\rm ve}$	6.928	6.932	6.937	6.942	6.946	6.951
$D_{\rm v}$	11.32	11.80	12.30	12.75	13.22	13.64
$D_{\rm d}$	5.747	7.294	10.75	14.29	21.80	33.08
$J_{\rm ve}^{\rm max}$	21.08	21.11	21.12	21.13	21.14	21.15
$\overline{J_{\rm ve}}$	1.270	1.270	1.270	1.270	1.270	1.270
$\tilde{J}_{\rm ve}$	8.89106	8.89112	8.89128	8.89138	8.89166	8.89205
$J_{\rm v}^{\rm max}$	31.10	31.43	31.56	31.63	31.67	31.71
$\overline{J_{\rm v}}$	1.900	1.911	1.924	1.935	1.947	1.958
$\tilde{J}_{\rm v}$	21.5853	22.5176	23.5551	24.4916	25.4893	26.3866

Table 8
Case 1: $N_{\rm ve} = 4,\ N_{\rm d} = 35,\ B = 10,\ fake\_no = 0.$

$N_{\rm v}$	46	48	50	52	54	56
$DR_{\rm v}$	1.182e−3	2.156e−3	3.940e−3	7.092e−3	1.145e−2	1.685e−2
η	0.6804	0.6828	0.6853	0.6879	0.6903	0.6922
$D_{\rm ve}$	3.609	3.614	3.618	3.625	3.630	3.636
$D_{\rm v}$	11.38	11.88	12.39	12.96	13.47	13.89
$D_{\rm d}$	30.85	46.62	73.46	117.9	183.3	267.1
$J_{\rm ve}^{\rm max}$	10.74	10.77	10.81	10.89	11.25	11.54
$\overline{J_{\rm ve}}$	1.212	1.212	1.212	1.212	1.212	1.212
$\tilde{J}_{\rm ve}$	4.4471	4.44753	4.44826	4.44958	4.45167	4.45445
$J_{\rm v}^{\rm max}$	31.11	31.37	31.42	31.60	31.66	31.71
$\overline{J_{\rm v}}$	1.977	1.988	2.000	2.009	2.019	2.028
$\tilde{J}_{\rm v}$	22.5856	23.5747	24.5533	25.6277	26.5729	27.3718

Table 9
Case 1: $N_{\rm ve} = 4,\ N_{\rm d} = 35,\ B = 10,\ fake\_no = 10.$

$N_{\rm v}$	44	46	48	50	52	54
$DR_{\rm v}$	1.166e−3	2.387e−3	3.877e−3	7.082e−3	1.171e−2	1.813e−2
η	0.6775	0.6802	0.6825	0.6850	0.6873	0.6894
$D_{\rm ve}$	3.603	3.608	3.613	3.618	3.624	3.630
$D_{\rm v}$	11.19	11.74	12.23	12.77	13.28	13.75
$D_{\rm d}$	13.63	20.83	31.01	49.57	79.83	123.1
$J_{\rm ve}^{\rm max}$	10.77	10.78	10.79	10.80	10.90	11.18
$\overline{J_{\rm ve}}$	1.212	1.212	1.212	1.212	1.212	1.212
$\tilde{J}_{\rm ve}$	4.44748	4.44773	4.44803	4.44866	4.44966	4.4512
$J_{\rm v}^{\rm max}$	31.05	31.37	31.39	31.58	31.65	31.70
$\overline{J_{\rm v}}$	2.058	2.072	2.085	2.098	2.108	2.118
$\tilde{J}_{\rm v}$	23.0339	24.2407	25.2785	26.4520	27.5218	28.5100

Table 10
Case 1: $N_{\rm ve} = 4,\ N_{\rm d} = 35,\ B = 10,\ fake\_no = 20.$

$N_{\rm v}$	42	44	46	48	50	52
$DR_{\rm v}$	1.313e−3	2.428e−3	4.447e−3	7.980e−3	1.287e−2	1.982e−2
η	0.6747	0.6771	0.6797	0.6824	0.6845	0.6870
$D_{\rm ve}$	3.600	3.605	3.609	3.615	3.619	3.625
$D_{\rm v}$	11.05	11.56	12.11	12.67	13.15	13.68
$D_{\rm d}$	5.821	7.665	11.15	17.43	27.41	43.12
$J_{\rm ve}^{\rm max}$	10.76	10.83	10.91	11.00	11.07	11.08
$\overline{J_{\rm ve}}$	1.212	1.212	1.212	1.212	1.212	1.212
$\tilde{J}_{\rm ve}$	4.4481	4.44828	4.44848	4.44877	4.44917	4.44982
$J_{\rm v}^{\rm max}$	31.19	31.32	31.48	31.57	31.64	31.70
$\overline{J_{\rm v}}$	2.131	2.147	2.163	2.180	2.192	2.208
$\tilde{J}_{\rm v}$	23.6900	24.9038	26.1632	27.4773	28.5840	29.8308

In a summary, if we want to improve the system throughput or the quality of voice and data services, B should be increased, at the price of degradation of the delay of video packets and its delay jitter. Tables 5–10 also suggest that it may be harsh for NPMA scheme to achieve some tighter real-time multimedia QoS requirement such as in [13], but generally it is tolerable [15]. This is interpreted as the consequence of the random-accessing mechanism applied on each transmission of CBR and VBR services rather than a promised one such as reservation.

Please see table 5 to inspect the performance of NPMA protocol with some fixed B ($B = 20$) and $fake\_no = 0$. The protocol operates normally yielding good throughput under this circumstances. Nevertheless, when the drop rate of voice packets gets close to 0.01, the jitter of voice packets has approached its upper bound (i.e., the maximum delay of voice), and delay of data packets approaches 100 ms which is considerable under 10 Mbps channel-transmission rate. Though this decentralized scheme with prioritization operates over broad area even without a base station, it

Table 11
Case 1: $N_{\mathrm{ve}} = 0,\ N_{\mathrm{d}} = 35$.

fake_no	N_{v}	DR_{v}	η	D_{v}	D_{d}	$J_{\mathrm{v}}^{\max}$	$\overline{J_{\mathrm{v}}}$	$\tilde{J}_{\mathrm{v}}$
0	166	4.004e−3	0.2381	14.24	66.70	31.73	0.7581	10.2686
	168	5.485e−3	0.2397	14.39	88.94	31.76	0.7599	10.4054
	170	5.396e−3	0.2424	14.57	89.99	31.77	0.7614	10.5576
	172	1.106e−2	0.2468	14.89	186.1	31.78	0.7687	10.9623
	174	1.284e−2	0.2468	14.92	202.6	31.81	0.7700	11.0130
10	166	5.054e−3	0.2374	14.37	44.09	31.75	0.7690	10.5466
	168	8.163e−3	0.2411	14.65	66.31	31.77	0.7739	10.8473
	170	8.866e−3	0.2428	14.77	75.73	31.79	0.7741	10.9290
	172	1.209e−2	0.2449	14.93	98.80	31.80	0.7781	11.1481
	174	1.532e−2	0.2464	15.04	127.3	31.82	0.7807	11.2932
20	166	6.276e−3	0.2366	14.48	21.14	31.78	0.7795	10.7930
	168	8.544e−3	0.2397	14.71	28.64	31.80	0.7825	11.0263
	170	1.095e−2	0.2414	14.84	37.81	31.81	0.7854	11.1915
	172	1.389e−2	0.2439	15.02	49.97	31.82	0.7893	11.4193
	174	2.152e−2	0.2461	15.20	88.76	31.83	0.7951	11.6993

results in imperfect allocation of the channel resource. This observation is based on the fact that data users endure long delay while the drop rate of video packets is zero (not shown in the table). We had tried to adjust the maximum holding time of video packets to increase its drop rate in the range from 0 to 0.001. However, the overall improvement is exiguous and this control mechanism runs dynamically (i.e., it is difficult to set the exact value of the delay bound always assuring the drop rate of video packets less than 0.001). As a result, additional QoS requirements, e.g., the maximum delay of data packets, or the delay jitter of voice traffic relative to that of video traffic, may further restrict the tenable population.

Now we consider the case in which some data users pretend to process the highest priority playing "fake" video users. The admissible number of voice users decreases by 2 according to table 6 as *fake_no* increases by 10. That is, a disturbance with traffic amount 10 × 5 K (one data node) $=$ 50 Kbps in average brings about degradation of supportable traffic amount 2 × 32 K (one voice node) $\times\ (1.0/(1.0 + 1.35))$ (fraction of time in *on* state) $=$ 27.23 Kbps in average. This implies the great sensitivity of NPMA protocol to disturbance. The hidden terminal problem [17] incurred by decentralized control scheme is thus anticipated to seriously impact the system performance. If we temporarily ignore this possibility, the NPMA scheme seems yet robust to the small amount of traffic breaking the operation rule, since all indices of performance are varied slightly.

When $N_{\mathrm{ve}} = 0$ as shown in table 11, throughput can only achieve about 0.25 due to the low utilization in one CAC accessed by voice users (as a result of the rule about "permission of contention"). This coincides with the upper bound implied in figure 6 when $T_{\mathrm{s}} = T_{\mathrm{c}} = 0.0001$. The only one benefit from being inactive of video users is the less skew through services on the voice traffic, which currently takes the highest priority. Increasing *fake_no* when $N_{\mathrm{ve}} = 0$ approximately causes a performance degradation with the same order as $N_{\mathrm{ve}} = 4$, but the corresponding improvement in delay of data is less. Therefore, compared to the case with $N_{\mathrm{ve}} = 4$, the depression of throughput without other tradeoffs implies the poor performance when there are no video users (more generally, no high-prioritized traffic with high source rate or great endurable delay). It is hence impossible for additional voice users to fully utilize the channel proportionally to the amount free by four video users. We can take the hint from this observation that as MPEG IV-type video source is developed and applied, more channel resource would be spent in the CR overhead due to the decentralized control scheme of NPMA than what is shown by our simulations.

Case 2. Communication with random noise

We model the random noise in practical wireless communications as with some moderate transmission bit-error rate through some coding or interleaving techniques. A video or voice packet received with errors is dropped, and an erroneous data packet associated with negative acknowledgment shall be scheduled for re-transmission. The number of bits in one video or voice packet in this case should decrease to avoid severe drop rate. That of data packets also needs to decrease in order not to cause rapid saturation of the channel. Therefore, we temporarily refer to an ATM-cell size and consider 500 bits in one packet. The transmission bit-error rate thus should not be larger than about $2 \cdot 10^{-6}$ to satisfy the QoS of video service. Associated parameters different from those applied in case 1 are consequently listed in table 4. Those not listed here remain the same value.

The value of B in table 4 is changed inversely proportionally to T to maintain the least overall length of the video transmission phase. Taking transmission errors into consideration generally decreases delay of voice packets and increases delay of data packets and voice delay jitter. The first fact can be explained by the raising drop rate of video packets. From tables 12 and 13, we observe that video drop rate keeps approximately constant at 0.0005, and the simultaneously supportable voice users decreases by about 18 (245 Kbps in average) from those in error-free cases. Please note that mean jitter and its second moment of video traffic is about half of that in error-free case. To explicate this interesting phenomenon, one has to comprehend that the jitter of video actually results from the effect of B when $B > 1$. If the constraint of the least buffer length of video users is relaxed, this would hardly become a problem since the video service has the highest priority. Therefore, the inclusion of transmission error improves the jitter distribution of video packets as some of them are dropped. Also the above conclusions require properly adjustment of B, which is decided to provide a fairly comparison between error-free and noisy communications.

As $N_{\mathrm{ve}} = 0$, the inclusion of the effect of random noise so severely impacts the operation of the system such that supportable number of voice users decreases by about 58,

Table 12
Case 2: $N_{\mathrm{ve}} = 4$, $N_{\mathrm{d}} = 35$, $B = 40$.

N_{v}	34	36	38	40	42	44
DR_{ve}	5.000e−4	4.963e−4	4.950e−4	4.985e−4	4.993e−4	4.937e−4
DR_{v}	1.678e−3	3.110e−3	5.774e−3	8.402e−3	1.329e−2	1.989e−2
η	0.6546	0.6569	0.6597	0.6619	0.6646	0.6668
D_{ve}	6.910	6.915	6.921	6.923	6.931	6.936
D_{v}	6.521	6.962	7.488	7.916	8.465	8.961
D_{d}	49.63	87.61	154.63	237.13	389.4	591.9
$J_{\mathrm{ve}}^{\max}$	20.94	20.91	20.94	20.99	20.90	20.91
$\overline{J_{\mathrm{ve}}}$	0.6507	0.6507	0.6507	0.6507	0.6507	0.6507
$\tilde{J}_{\mathrm{ve}}$	4.450	4.451	4.452	4.452	4.454	4.455
$J_{\mathrm{v}}^{\max}$	31.26	31.64	31.69	31.72	31.74	31.77
$\overline{J_{\mathrm{v}}}$	1.711	1.973	2.353	2.715	3.249	3.813
$\tilde{J}_{\mathrm{v}}$	14.53	19.17	25.78	32.04	41.24	50.88

Table 13
Case 2: $N_{\mathrm{ve}} = 4$, $N_{\mathrm{d}} = 35$, $B = 20$.

N_{v}	30	32	34	36	38	40
DR_{ve}	5.009e−4	5.007e−4	5.066e−4	4.972e−4	4.997e−4	4.994e−4
DR_{v}	1.627e−3	2.905e−3	5.559e−3	1.010e−2	1.603e−2	2.394e−2
η	0.6488	0.6514	0.6541	0.6565	0.6591	0.6612
D_{ve}	3.580	3.586	3.592	3.598	3.604	3.609
D_{v}	6.318	6.849	7.422	7.981	8.597	9.141
D_{d}	54.89	110.3	194.1	339.2	549.8	845.3
$J_{\mathrm{ve}}^{\max}$	10.76	10.79	10.83	10.92	11.28	12.14
$\overline{J_{\mathrm{ve}}}$	0.6353	0.6353	0.6353	0.6353	0.6353	0.6353
$\tilde{J}_{\mathrm{ve}}$	2.22763	2.22864	2.22997	2.23142	2.23342	2.23553
$J_{\mathrm{v}}^{\max}$	30.15	31.66	31.67	31.69	31.73	31.78
$\overline{J_{\mathrm{v}}}$	1.841	2.108	2.477	2.959	3.547	4.164
$\tilde{J}_{\mathrm{v}}$	14.2728	19.1446	25.7576	34.1950	44.5015	55.1820

Table 14
Case 2: $N_{\mathrm{ve}} = 0$, $N_{\mathrm{d}} = 35$.

N_{v}	106	108	110	112	114	116
DR_{v}	3.745e−3	4.652e−3	6.333e−3	9.000e−3	1.197e−2	1.422e−2
η	0.1513	0.1529	0.1557	0.1585	0.1610	0.1626
D_{v}	7.983	8.119	8.382	8.649	8.908	9.082
D_{d}	187.4	234.5	342.2	496.1	694.8	801.5
$J_{\mathrm{v}}^{\max}$	31.71	31.75	31.76	31.78	31.78	31.81
$\overline{J_{\mathrm{v}}}$	1.349	1.483	1.768	2.092	2.443	2.682
$\tilde{J}_{\mathrm{v}}$	16.1575	18.3494	23.0024	28.2924	33.9878	37.8828

and the throughput is much lower. Delay of data packets is even higher, and the voice jitter is still beneath the QoS of some applications [13]. The system is more unstable and sensitive to noise and interference compared to the case with $N_{\mathrm{ve}} = 4$. This is still due to the store-and-forward transmission scheme required for the decentralized CR procedure in NPMA, which degenerates to be the single-hop scheme (i.e., transmitting one packet in one CAC) as video traffic vanishes.

5. Conclusions

The NPMA protocol standardized by ETSI is a sort of multi-access protocol with two CR layers as indicated in this paper. The generalization of its prioritization phase into randomly addressing phase (which is mathematically equivalent to orthogonal signaling in RAP protocol) provides an additional CR layer to enhance the collision resolution capability. Performance of both random access protocols is evaluated, with original NPMA scheme supporting integrated services and the generalized version managing single-type traffic (data traffic) only. In the latter, we have investigated the effectiveness of its CR capability, while the throughput/delay performance can be improved only if the utilization of the transmission phase in one CAC is high enough. This restraint results from the long overhead required for the decentralized controlled CR of NPMA, and also suggests to us the store-and-forward transmission scheme in simulations about integrated traffic.

The performance of NPMA is acceptable when there are some active video users, while an additional “least-buffer-length” constraint on video users is indispensable, and delay of data packets is relatively long due to the prioritization scheme synthesizing all VBR and CBR traffic into contention processes. The “least-buffer-length” constraint can only applied on the traffic with high source rate and greatly endurable delay, so the less-prioritized services such as voice and data in our case must join the contention as long as they become active considering their delay performance. Consequently, when there is no video traffic, the system yields unsatisfactory throughput/delay performance because the store-and- forward transmission scheme degenerates to a single-hop case and much more bandwidth is consumed in the CR overhead. Appropriate mechanism to improve system behavior is needed. A general centralized multi-layer CR random access protocol in wireless networks which yields short CR overhead is thus under research.

The influence of the disturbance came from some data users (least-prioritized) pretending to be highest-prioritized to gain more channel resource is also considered. In section 4, the sensitivity of NPMA protocol accounting for this imperfect situation has been explored that 100% amount of disturbance approximately results in 50% loss of supportable amount of traffic. Although the slight variation in performance indices suggests the robustness of NPMA scheme, the hidden terminal problem incurred by distributed control schemes which is not considered in our evaluation is anticipated to cause serious problems in the NPMA operation.

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