Performance of DSMA/CD in CDPD Networks

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Abstract

Cellular Digital Packet Data (CDPD) is a technology that has enabled data transmission and services during many years. CDPD utilizes same radio resources as cellular phone networks. The channel between mobile equipments and a mobile data base station is controlled using Digital Sense Medium Access with Collision Detection (DSMA/CD). The special feature of DSMA/CD is that the status of the channel cannot be sensed directly. This paper focuses on the implementation and throughput of DSMA/CD in CDPD networks. Throughput is analyzed using previously known analytical models. Also a simulation model and some proposed enhancements are introduced briefly.

1 Introduction

In Cellular Digital Packet Data (CDPD) networks free capacity of voice channels of cellular voice systems is utilized. Multiple mobile end systems share one channel to the mobile data base station, so some medium access procedure is needed.

CDPD technology uses Digital Sense Multiple Access with Collision Detection (DSMA/CD) as an access protocol. DSMA/CD is quite similar to the non-persistent Carrier Sense Multiple Access with Collision Detection (CSMA/CD). The difference is that in CDPD networks the status of the shared channel cannot be sensed directly. The status of the reverse channel is founded out using special flags on the forward channel. Because these flags are carried on the forward channel only once in 60 bits, the protocol is called digital.

This paper focuses on the throughput analysis of DSMA/CD in CDPD networks specially. The rest of paper is organized as follows: Section 2 presents the architecture of CDPD networks. Section 3 introduces DSMA/DT protocol. In the fourth section both an analytical model and a simulation model from the literature are presented and the numerical results are analyzed. Section 5 presents some proposed enhancements. Finally, the last section is short conclusion.

2 CDPD Networks

Cellular Digital Packet Data is quite simple and cheap solution to enable data services using same radio frequencies as existing cellular networks use. In the following sections the basic principles of CDPD are studied, specially on MAC and physical layer.

2.1 Network architecture

The idea of Cellular Digital Packet Data (CDPD) technology is to utilize same radio frequencies, which are used by telephone cellular networks like Advanced Mobile Phone Service (AMPS). The architecture of CDPD system is specified in details in [1]. CDPD technology has already been many years in wide use, mainly in US [2]. The following description of CDPD is based on [1] and [2].

CDPD extends existing data communication networks to network layer (layer 3), see Figure 1. So existing network layer applications like e-mail services are immediately available for CDPD users without any gateway services. Also integration of CDPD network to external networks is done using existing network layer protocols.

The key elements of CDPD system are the end systems (ESs), the intermediate systems (ISs) and the mobile data base station (MDBS). ESs exchange information and act as end nodes of the network. The end system can be mobile (M-ES) or fixed (F-ES). An M-ES consists of a mobile terminal and a CDPD radio modem. The function of the CDPD radio modem is to connect mobile terminal to radio link and its protocols.

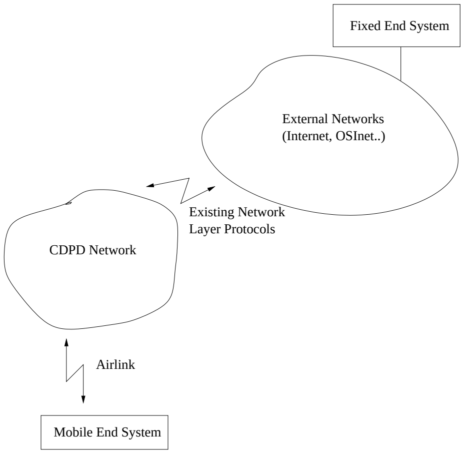

Figure 1: The CDPD network as an extension of other networks, adapted from [1].

ISs store, forward and route information. There are two type of ISs: generic IS and mobile data IS (MD-IS). A generic IS may be normal router, whereas MD-IS is specialized to route data to M-ESs, which location can change.

The MDBS can be compared to a common cellular base station. The function of the MDBS is to exchange data link information between M-ESs and MD-ISs. In other words, MDBS manages air interface between M-ESs and the CDPD backbone. The MDBS manages also radio resource procedures like channel hopping.

2.2 MAC-layer

Multiple ME-Ss share a single MDBS and direct communication is allowed only between an ME-s and an MDBS, not between ME-Ss. Information between ME-S and MDBS is transmitted over one pair of RF channels. The channel from MDBS to ME-S is referred to as *forward channel* and the channel from M-ESs to MDBS is referred to as *reverse channel*. These channels together are called as a *CDPD channel stream* (see Figure 2). Transmission rates of both forward and reverse channels are 19.2 kbit/s.

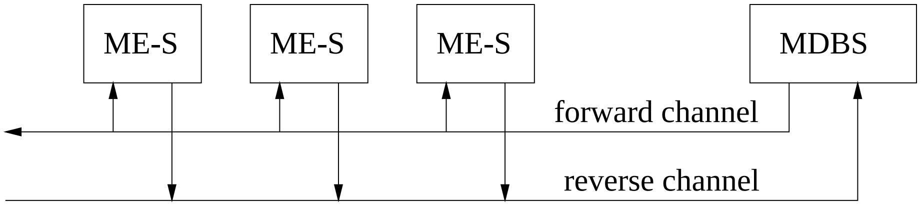

Figure 2: The CDPD channel stream, adapted from [1].

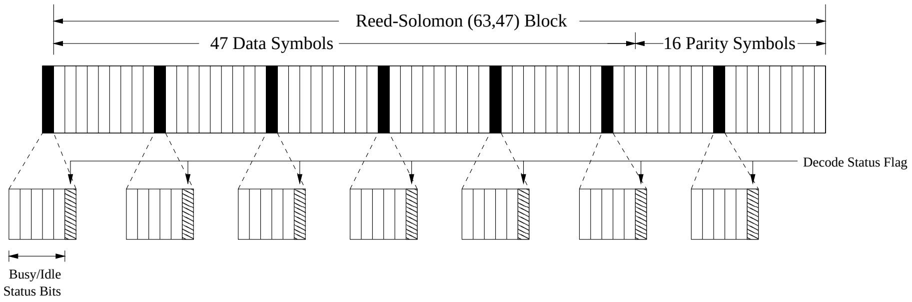

Figure 3: The CDPD forward channel, adapted from [1].

2.2.1 Forward channel

Data is transmitted over radio channel in frames, which consist of variable number of octets. Frames are transmitted as a burst of blocks interleaved with control flags and synchronization words [3]. Data blocks are encoded using (63,47) Reed-Solomon (RS) error coding code. Totally each block consists of 378 bits.

In Figure 3 is described the forward channel transmission structure. The channel consists of RS-blocks and control flags. Each control flag are build up from one *decode status flag* and exclusive-OR of the forward synchronization word (FSW) and busy/idle status bits (5 bits).

2.2.2 Reverse channel

Figure 4 describes the structure of transmission on reverse channel. The reverse channel transmission burst consists of the dotting sequence, the reverse synchronization word and one or more blocks. The continuity indicator of each block indicates termination or continuation of the burst. After RS-blocks there

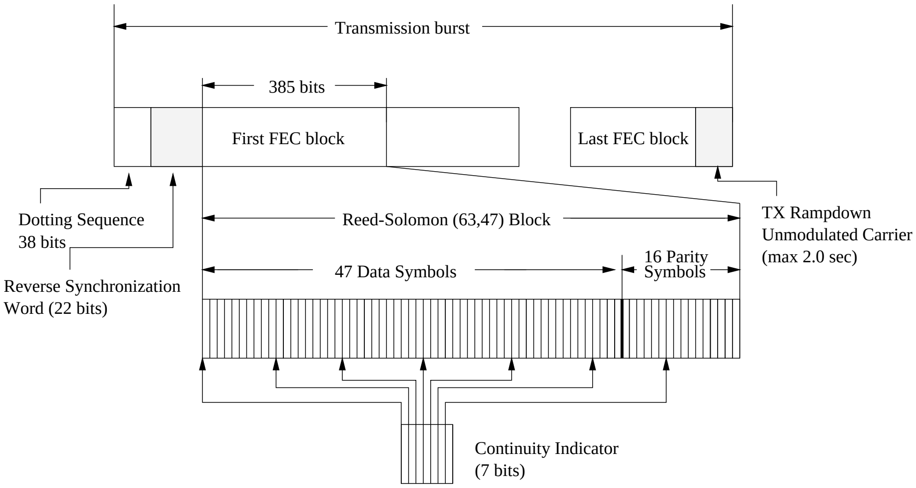

Figure 4: The CDPD reverse channel, adapted from [1].

is a transmitter ramp down.

ME-S is allowed to start transmission on the reverse channel only at the beginning of a microslot. The microslot is defined as time between the beginning of transmission of one ME-S and time when other ME-Ss sense the channel busy status. In CDPD technology, the length of microslot is fixed to 60 bits (3.125 ms).

3 DSMA in CDPD networks

An M-ES may access the reverse channel using an access protocol which is quite similar to the Carrier Sense Multiple Access with Collision Detection (CSMA/CD). When an M-ES want to transmit data to MDBS, it starts to sense the reverse channel. However, in CDPD the status of the reverse channel cannot be sensed directly by M-ESs, because reception and transmission frequencies are different.

An M-ES utilizes decode and busy/idle status flags of the forward channel to find out the current status of the reverse channel. These flags are transmitted over the forward channel only once every 60 bits. So the access scheme mechanism applied to these circumstances is called Digital Sense Multiple Access with Collision detection (DSMA/CD).

An M-ES that has a message ready for transmission senses the busy/idle flag. If the channel is idle, the M-ES starts transmission within 8 bit interval from the end of busy/idle flag. If the channel is sensed busy, the M-ES defers for a random number of microslots and after that start to sense the busy/idle flag again. Since the M-ES stops the sensing for a while, the protocol is *non-persistent*. The distribution of waiting time in the defer mode is uniform.

Once M-ES has gained access to the reverse channel, it continues transmission, until the decode status flag on the forward channel indicates that the MDBS has encountered decoding failure. The decoding failure is a consequence of a collision in the reverse channel or channel impairments. After the detection of decoding failure, the M-ES stops transmission and goes to the backoff mode.

The M-ES is in backoff mode a random time period and after that it begins the sensing busy/idle flags again. The time period in backoff mode is determined by exponential backoff algorithm. In the exponential backoff algorithm the mean length of the waiting period increases exponentially after each retransmission attempt and the number or retransmission attempts is limited.

4 Throughput analysis of DSMA/CD

Many paper have studied the performance DSMA/CD. Paper [4] constructs a Markov model for the reverse channel, where an aggregate Poisson arrival process is assumed. Also paper [5] presents a expression for throughput as a function of offered load (including new packets and retransmissions). In paper [3] the arrival of new packets and retransmissions are separated, which enables more detailed analysis. So the following analytical model of DSMA/CD is completely based on paper [3].

4.1 Analytical model of DSMA/CD

Let N be the number of M-ESs, which share single channel using DSMA. The channel is divided into time slots equal to one microslot, where the length of one microslot is 60 bits. Channel impairments cause blocking by rate ϵ. In CDPD networks, the acceptable error-blocking rate is 0.05.

The state of M-ES can be idle or active. In the idle state in any slot a new packet is generated with probability α. In active state, a M-ES can be transmitting, in defer or in backoff mode. In analysis of paper [3], both defer and backoff classes are treated in same way, paper refers these two classes together as a backlogged class. Each backlogged user senses the busy/idle status of the channel with probability β so the mean delay between retransmission attempts is β. This differs from actual $CDPD$ behavior where the retransmission delay follows the exponential backoff algorithm.

In CDPD specification [1] each frame contains m blocks, where $m \in [1..4]$. Since the length of each block is 385 bits and the length of dotting sequence and synchronization together is 60 bits, the length of the frame of m blocks in μ microslots is $\tau = \frac{385m \text{ bits}}{60 \text{ bits}} + \frac{385 \text{ bits}}{60 \text{ bits}} = [6.41m] + 1$.

The channel time can be divided into idle and transmission periods, which together are called as a cycle. Let I and T be the lengths of idle and transmission periods respectively. In the case of the successful transmission, the length of the transmission period is the message length in microslots plus one microslot for avoidance of collision at the end tail of the message that is $T = (\tau + 1)$. If transmission is unsuccessful, $T = (\tau_c + 1)$ where τ_c is a collision window. The length of the collision window depends on the block, in which the collision occurs. If the collision occurs in the ith block, $\tau_c(i) \simeq 15 + 7(i-1)\mu$ slots.

Let $N(t)$ denote the number of backlogged users at time t. $N(t)$ as a random variable describes the state of the system at time t. Let t_0 denote the start of some idle period. During the idle period, the state of system does not change therefore $N(t) = N(t_0)$ for all $t \in [t_0, t_0 + I - 1]$. If some user becomes ready during slot $t_0 + I - 1$, it senses the channel idle and starts its transmission at the beginning of the next slot (slot $t_0 + I$).

The system can be modelled as an embedded Markov chain, where each embedded point is the first microslot of a cycle. Let $\pi = [\pi_1, \pi_2, ..., \pi_n]$ be the steady-state probability distribution of $N(t)$ and $P = [p_{ij}]$ be the transitional probability matrix, where

$$p_{ij} = P[N(t_0 + I + T) = j | N(t_0) = i]. \tag{1}$$

The steady-state probabilities can be solved from equation

$$\pi P = \pi. \tag{2}$$

Paper [3] formulates probability matrix P through probability matrices $S =$

$[s_{ij}]$, $F(k) = [f_{ij}]$, $b = [b_{ij}]$ and $Q = [q_{ij}]$, where

$$s_{ij} = P[N(t_0 + I) = j \text{ and transmission is successful } |N(t_0 + I - 1) = i]$$
$$= \begin{cases} 0, \text{ if } j < i, \\ (1-\epsilon)^m (1-\alpha)^{N-i} i\beta(1-\beta)^{i-1}/(1-\delta_i), \text{ if } j = i, \\ (1-\epsilon)^m (N-i)\alpha(1-\alpha)^{N-i-1}(1-\beta)^i/(1-\delta_i), \text{ if } j = i+1, \\ 0, \text{ otherwise}, \end{cases} \tag{3}$$

$$f_{ij}(1) = P[N(t_0 + I) = j \text{ and decoding failure in the first block } |N(t_0 + I - 1) = i]$$
$$= \begin{cases} 0, \text{ if } j < i, \\ [(1-\alpha)^{N-i}[1-(1-\beta)^i - i\beta(1-\beta)^{i-1}] + \\ \epsilon[(1-\alpha)^{N-i} i\beta(1-\beta)^{i-1}]]/(1-\delta_i), \text{ if } j = i, \\ [(N-i)\alpha(1-\alpha)^{N-i-1}[1-(1-\beta)^i] + \\ \epsilon[(N-i)\alpha(1-\alpha)^{N-i-1}(1-\beta)^i]]/(1-\delta_i), \text{ if } j = i+1, \\ \binom{N-i}{j-i}(1-\alpha)^{N-j}\alpha^{j-i}/(1-\delta_i), \text{ otherwise}, \end{cases} \tag{4}$$

$$f_{ij}(k) = P[N(t_0 + I) = j \text{ and decoding failure in } k\text{th block, } k > 1 \ |N(t_0 + I - 1) = i]$$
$$= \begin{cases} 0, \text{ if } j < i, \\ (1-\epsilon)^{k-1}\epsilon[(1-\alpha)^{N-i} i\beta(1-\beta)^{i-1}]/(1-\delta_i), \text{ if } j = i, \\ (1-\epsilon)^{k-1}\epsilon[(N-i)\alpha(1-\alpha)^{N-i-1}(1-\beta)^i]/(1-\delta_i), \text{ if } j = i+1, \\ 0, \text{ otherwise}, \end{cases} \tag{5}$$

$$b_{ij} = P[\text{ The number of backlogged users changes from } i \text{ to } j \text{ during any busy slot }]$$
$$= \begin{cases} 0, \text{ if } j < i, \\ \binom{N-i}{j-i}(1-\alpha)^{N-j}\alpha^{j-i}, \text{ otherwise}, \end{cases} \tag{6}$$

and

$$
\begin{aligned}
q_{ij} &= P[N(t_0+I) = i-1 | N(t_0+I-1) = i \text{ and successful transmission }] \\
&= \begin{cases} 1, \text{ if } j = i-1, \\ 0, \text{ otherwise.} \end{cases}
\end{aligned}
\tag{7}
$$

Now the probability matrix P is

$$
P = SB^{\tau+1}Q + \sum_{k=1}^{m} F(k)B^{\tau_c(k)+1}. \tag{8}
$$

Finally, channel throughput is the ratio of average time the channel is carrying successful transmission (T_s) and average cycle length (T_c):

$$
S = \frac{T_s}{T_c}, \tag{9}
$$

$$
T_s = \sum_{i=0}^{N} P_s(i)(\tau+1), \tag{10}
$$

$$
T_c = \sum_{i=0}^{N} \pi_i[\frac{1}{1-\delta_i} + P_s(i)\tau + \sum_{k=1}^{m}\sum_{j} f_{ij}(k)\tau_c(k) + 1], \tag{11}
$$

where $P_s(i)$ is the probability that the transmission is successful if the number of backlogged users in the beginning of the cycle is i,

$$
P_s(i) = (1-\delta_i)^{-1}(1-\epsilon)^m[(N-i)\alpha(1-\alpha)^{N-i-1}(1-\beta)^i + i\beta(1-\beta)^{i-1}(1-\alpha)^{N-i}]. \tag{12}
$$

4.2 Numerical results

When generated traffic per M-ES is α and μ is chosen to be one, the total traffic load assigned to the channel is αN (excluding retransmissions). The throughput as a function of generated traffic is presented in Figure 5. The number of M-ESs is 10 and the frame size changes from one to four. The maximum throughput is achieved when α is approximately 0.01. Increasing the number of blocks in a frame improves throughput.

If the retransmission probability is β the mean delay to the next retransmission attempt is $1/\beta$. If β is small, the waiting times for next sensing is long and

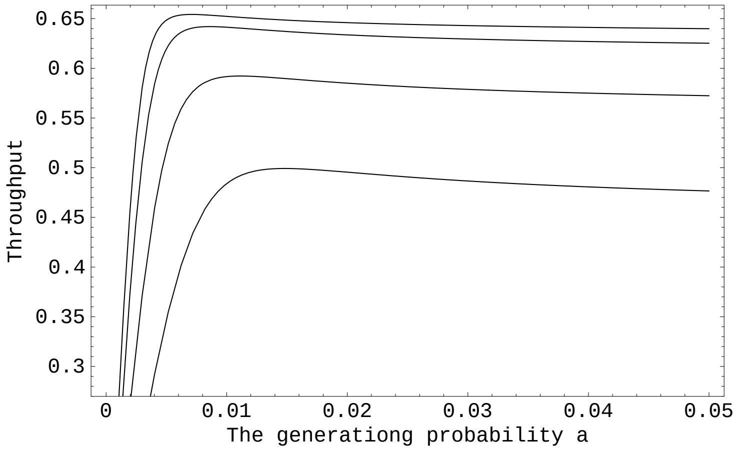

Figure 5: Throughput as a function of α when $m = 1$ (the lowest line), $m = 2$, $m = 3$ and $m = 4$ (the topmost line). $N = 10$, $\beta = 1/20$ and $\epsilon = 0.05$.

there are not so much collisions. However, sometimes the channel can be idle even there is something to send. This wastes the capacity. Also the total delays are unnecessary long. When β is greater, retransmissions delays are smaller and there is not so much these wasted slots. However, the probability to collision is great. In Figure 6 we can see that the optimal level for β is approximately 0.04, when α is 0.01.

Also the error-blocking rate has an effect on throughput. In Figure 7 the throughput is presented as a function of α using different block-error rates. As expected, the throughput decreases when block-error rate increases.

4.3 Simulation study of DSMA/CD

Paper [6] studies the performance of DSMA with collision detection by a computer simulation. The hierarchical simulation model is based on the CDPD Specification 1.1. It does not take noise or fading into account. However, the user queue size is limited in part of simulation cases.

The system model is as follows: There are N users sharing one channel. Each user has a queue with capacity Q_c. Messages are broken into frames with length MAX_FRAME_LENGTH. The queue of each user consists of two parts: Waiting Queue (WQ) and Transmission Queue (TxQ). New packets are

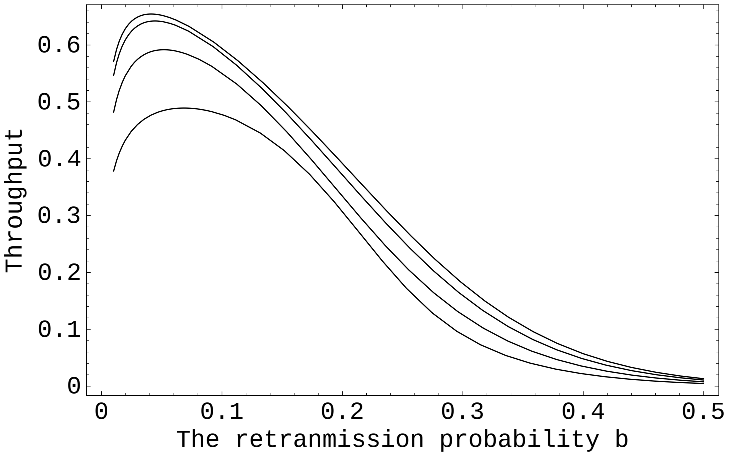

Figure 6: Throughput as a function of β when $m = 1$ (the lowest line), $m = 2$, $m = 3$ and $m = 4$ (the topmost line). $N = 10$, $\alpha = 0.01$ and $\epsilon = 0.05$.

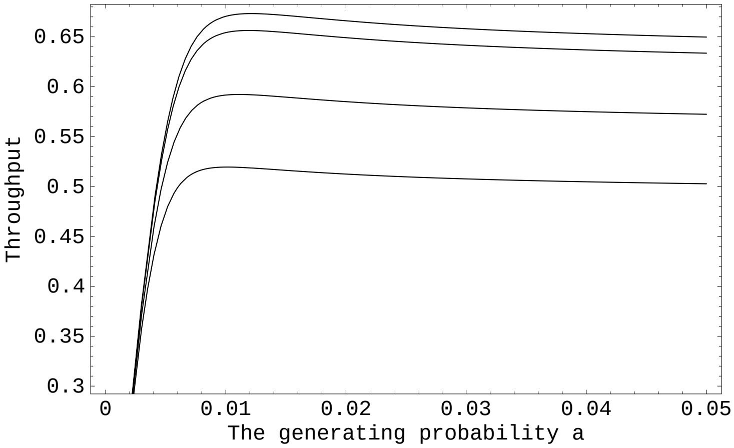

Figure 7: Throughput as a function of β when $\epsilon = 0.1$ (the lowest line), $\epsilon = 0.05$, $\epsilon = 0.01$ and $\epsilon = 0$ (the topmost line). $N = 10$, $\alpha = 0.01$ and $m = 2$.

put to WQ. Packets that are ready for transmission are in TxQ. When TxQ is empty, all frames from WQ are put to TxQ. When channel is sensed to be idle, user starts transmission from TxQ. MAX_BLOCKS blocks are permitted to transmit at a time.

If channel is busy or transmission was unsuccessful the user waits a period defined by a exponential backoff algorithm. The maximum number of attempts is defined by $MAX\_TX\_ATTEMPTS$. Mobile generated load MGL is average number of bits arriving to one M-ES during one bit time. Mobile offered load MOL and channel offered load COL are average number of bits accepted into one M-ES and all M-ESs respectively.

The performance indices in paper [6] are throughput, data delivery time and the service grade. Frame delivery and message delivery time refer to the average system time of successful frame and message respectively. The frame service grade and message service grade are the proportions of frames and messages, which are successful.

As a result of simulations, paper [6] finds that the maximum channel throughput is approximately 0.65 in all simulation scenarios. This is almost same as the maximum throughput calculated by the analytical model in Section 4. The maximum frame delivery time is upper bounded by a constraint. Surprisingly, the frame delivery time does not differ from message delivery time significantly and also frame service and message service grades are almost equal.

5 Proposed enhancements to DSMA protocol

Many MAC-protocols that are developed to wireless networks like R-ALOHA assume that the signal propagation delay and the processing delay together are quite small when compared to the transmission delay. However, in high-speed networks the transmission delay is shorter and the MAC-protocols with previous assumptions become inefficient. Paper [7] proposes a new MAC-protocol, DSMA with Delayed Transmission (DSMA/DT), which should not suffer from long propagation delays enormously. The following description of DSMA/DT follows paper [7].

Let the round-trip signal propagation delay plus processing delay referred to as the round-trip delay, denoted by T. Busy/Idle status flags are denoted in [7] by B and decode flags by D. The round-trip delays of B and D flags are assumed to be identical. This is valid in high-speed networks, where the propagation delay is a major component of the total round-trip delay. When round-trip delay is long, the performance of pure DSMA is decreased due to unawareness of ongoing transmissions and long delay of stopping transmission in the case of collision.

The key idea of DSMA/DT is that the users send only a part of packets when find the channel idle. The packets are divided into data blocks and the channel time is divided into slots according to the carrying time of one data block. As explained in previous sections, B and D flags on the forward channel indicate the status of the reverse channel. B is 1 if data is received by MDBS and zero otherwise. D is one if a data block is successfully decoded by MDBS and zero otherwise.

The behavior of DSMA/DT is as follows: The user senses the channel and if it finds channel idle (B=0) it sends a data block in the next time slot. The user continues to listen channel and if (1) the D flag does not indicate any successful decoding (D=0) for next T-1 slots and (2) D flag is one for the slot T, the transmission of the first data block has been successful and the channel is seized by the user. Now the user can send the rest of the packet. When the channel is seized, the base station sets B to one for the next T time slots to avoid collision in the latter transmission.

If condition (1) is true but condition (2) is false, the data block of the user is may collided with some other block and user has to wait a period defined by exponential back-off procedure. If condition (1) is false for any of T-1 time slot (the flag D is one), the channel is already seized by some other, and user has to defer its transmission with a random delay. The behavior of DSMA/DT can be viewed as a reservation protocol, where the first data block of a user represents reservation request.

Paper [7] presents also some additional features to proposed DSMA/DT protocol. The first feature is related to the unnecessary long idle periods. When some user has stopped transmission it takes T time slots to set flag B to zero and the channel sensed to be idle by other users. Therefore DSMA/DT still suffers from long round-trip delays. The method introduced in [7] to avoid this waste of bandwidth is the use of the length indicator bit (denoted by I) in each data block. The user sets bit I to 1 if the transmission of the rest of a packet takes longer than T time slots and to 0 otherwise. B flag is then set to 0 according to I flag.

The second feature of paper [7] to enhance the performance of DSMA/DT is seizure queueing (SQ). The idea of improvement is to put the users that have received their first data blocks successfully to the queue and transmit their remaining data in the order of the channel seizure. In this protocol additional flag (denoted by E) is needed. When user sets the flag E to one the packet transmission is in the end.

The protocol with seizure queuing operates as follows: When user senses the channel idle, it transmits its first data block and sets a local variable Q to zero. Q represent the queueing position of the user. As in DSMA/DT protocol, user senses the channel during T-1 time slots and updates queueing position by setting $Q = Q + D$, because every $D = 1$ means that some other user has received his first data block successfully and seized the channel. After the own channel seizure, the user updates his queueing position by setting $Q = Q - E$, because each $E = 1$ indicates that some user has stopped his transmission. When Q is zero, user should start to transmit the rest of his packet.

Paper [7] studies analytically the throughput of DSMA/DT and its improved versions. Numerical examples show that the use of delayed transmission improves throughput of DSMA significantly specially when the aggregated offered traffic is heavy. DSMA/DT with the length indicator bit and seizure queueing improves throughput even more. However, if the comparisons had included also DSMA/CD, the improvements would not have been so remarkable.

6 Conclusion

CDPD is quite simple and flexible technology to bring data services to the end user in the cellular phone networks. CDPD utilizes the capacity that is reserved cellular networks but remains unused.

In CDPD networks multiple mobile terminals share one channel to the base station. However, the status of the channel cannot be sensed directly. The access protocol in CDPD networks is a modified version of CSMA/CD, namely DSMA/CD that uses busy/idle and decode flags on the forward channel to analyze the status of the reverse channel. Because these decode and busy/idle flags are carried only once in the 60 bits, sensing is ”digitalized”.

Analytical models of DSMA/CD are developed in many papers. For example, the arrival rate, retransmission intensity and channel error-blocking rate have an influence on throughput. However, the maximum throughput achieved by both analytical models and simulations is approximately 0.65.

DSMA/CD may suffer from long propagation delays. One proposition to overcome this problem is to use the first data block of the transmission as a reservation request.

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