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Performance of CDPD with Timed Hop and Forced Hop

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Abstract. *Cellular Digital Packet Data* (CDPD) offers mobile users access to a low-cost, ubiquitous, wireless data network. CDPD can be overlaid on existing AMPS analog cellular systems and share their infrastructure equipment on a non-interfering basis. To prevent interference with the voice activities, CDPD performs forced hop to a channel stream when a voice request is about to use the RF channel occupied by that channel stream. In addition, several timers and system parameters are defined in CDPD to ensure that the normal AMPS activities are not affected by CDPD. This article investigates how the channel selection algorithms, the timers and other parameters affect the performance of AMPS/CDPD systems. Specifically, we study the trade-off between mean CDPD channel holding time and voice incompletion probability. Our study indicates that if AMPS exercises the most-idle channel selection algorithm and CDPD exercises the least-idle channel selection algorithm, then the largest mean CDPD channel holding time is expected. On the other hand, if AMPS exercises the least-idle channel selection algorithm, then the smallest voice incompletion probability is expected.

Keywords: Cellular Digital Packet Data, channel selection algorithm, forced hop, timed hop

1. Introduction

Cellular Digital Packet Data (CDPD) [1,3,4,7,9–11] networks provide wireless data communications services to mobile users by sharing the radio equipment and unused RF channels with Advanced Mobile Phone Service (AMPS) [5]. CDPD uses idle RF channels of AMPS to transmit packet data, and autonomously releases the occupied RF channel when this channel is about to be assigned for a voice request.

Figure 1 illustrates the CDPD network architecture. Mobile End System (M-ES) is a subscriber device that enables a CDPD user to communicate with CDPD network. The physical location of M-ESs may change from time to time, but continuous network access is maintained. Mobile Data Base Station (MDBS) is responsible for detailed control of the radio interface, including adjustment of M-ES transmission power levels, allocation of radio channels, interoperation with cellular voice channel usage, and radio media access control. In order to share radio resources with the cellular system, an MDBS is expected to be co-located with an AMPS base station (BS). Furthermore, MDBSs may share cellular equipment (such as antennas for transmitters and receivers) to communicate with the M-ESs. Mobile Data Intermediate System (MD-IS) connects to several MDBSs via wired links or microwaves. MD-ISs are responsible for CDPD activities such as authentication and connection management. They also support user mobility (by exchanging user location information with other MD-ISs), and route the incoming data frames to destinations based on the knowledge of user location.

An M-ES communicates with an MDBS through an RF channel not used by AMPS (referred to as a *CDPD channel stream*). A CDPD channel stream can be shared by several M-ESs.

An MDBS is allocated a frequency pool that contains a subset of frequencies of the associated AMPS BS. The MDBS utilizes the radio resource management entity (RRME) to select and assign an RF channel for each channel stream configured for that MDBS. To determine the frequencies in the CDPD frequency pool, a channel status protocol (CSP) is implemented [10]. Through the CSP message exchange, the CDPD system communicates with the AMPS system to update the shared channel status, which prevents both systems from choosing the same frequency at the same time. Alternatively, the MDBS may employ a sniffer that periodically scans the shared channels to identify the availability status of these RF channels. In this approach, CDPD determines the channels in the CDPD frequency pool without the involvement of AMPS (in other words, the AMPS system does not notice the existence of the CDPD system who shares the AMPS resources).

When a voice call arrives at an AMPS BS, the AMPS system selects an idle RF channel to serve this incoming voice request. If this RF channel is occupied by a CDPD channel stream, then the MDBS must relinquish this RF channel within 40 ms. This action is called *forced* or *emergency hop*. The MDBS then tries to re-establish the forced-hopped channel stream on another idle RF channel. If no such channel is available, then the forced-hopped channel stream enters a *blackout* period [2] until an RF channel is reassigned to this channel stream. In the CSP implementation, the hop procedure is exercised at the CDPD system when the AMPS system sends a channel busy message to the CDPD system, which indicates that the specific RF channel is about to serve voice traffic [10].

The MDBS also periodically performs channel switching (referred to as *timed* or *planned hop*) to avoid *channel sealing* or *channel stealing*. When the AMPS system notices the interference on a channel (due to CDPD activities on this channel), the channel is sealed and becomes unavailable to a voice user. In this case, CDPD steals the channel from the AMPS system. To avoid sealing of an RF channel, the MDBS uses timed hops to switch a CDPD channel stream periodically. In the timed hop mechanism, a *dwell timer* is defined for each shared RF channel to specify the

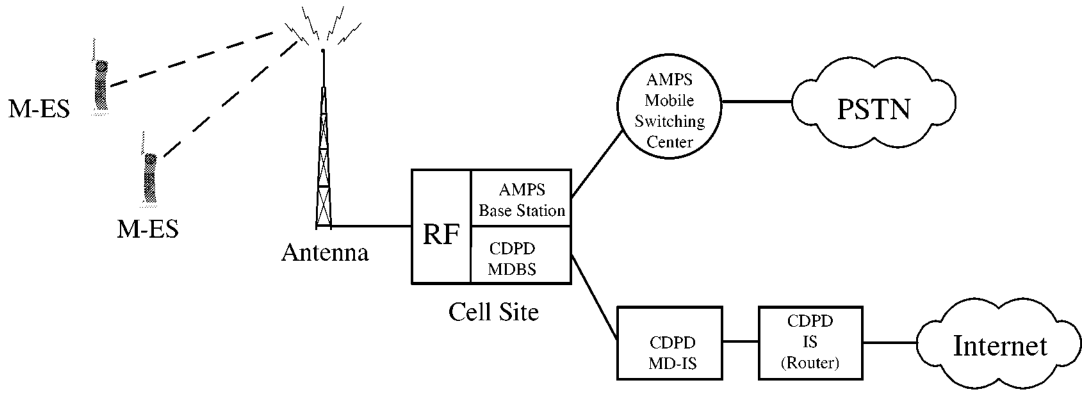


Figure 1. The CDPD network architecture.

period for which the channel stream can use the RF channel before a timed hop is performed. On the expiration of this timer, the MDBS RRME invokes the timed hop procedure to switch the CDPD channel stream to another RF channel. Specifically, the MDBS sends a switch channel message to the M-ESs of the CDPD channel stream through the old RF channel. Then it ceases transmission on the channel stream and tunes to the new frequency within 40 ms. The shared RF channels are also configured with a *layoff timer*. After a timed hop, the released RF channel cannot be used for CDPD before its layoff timer expires. This timer prevents a blackout CDPD channel stream from selecting an RF channel just released by CDPD. The dwell and layoff timers and the other system parameters are defined in the CDPD specifications [3].

Since switching a CDPD channel stream from an RF channel to another is an expensive operation, it is important to exercise an appropriate channel selection algorithm (under the constraint that AMPS does not notice the existence of CDPD) to minimize the number of CDPD channel switchings or to maximize the CDPD channel holding time t_a (the period that an RF channel is utilized by a CDPD channel stream before a channel hop occurs on this channel).

Consider an idle RF channel with respect to voice usage (i.e., the channel is not used by AMPS but may or may not be used by CDPD). This channel is called the most-idle (least-idle) channel if the channel has not been utilized by AMPS voice user for the longest (shortest) time. Four channel selection algorithms are investigated in our study.

- MM (most–most). When AMPS needs a voice channel, it selects the most-idle channel. When CDPD needs a data channel, it selects the most-idle channel currently not used by CDPD and not in layoff state.
- LL (least–least). When AMPS needs a voice channel, it selects the least-idle channel. When CDPD needs a data channel, it selects the least-idle channel currently not used by CDPD and not in layoff state.
- LM (least–most). When AMPS needs a voice channel, it selects the least-idle channel. When CDPD needs a data channel, it selects the most-idle channel currently not used by CDPD and not in layoff state.
- ML (most–least). When AMPS needs a voice channel, it selects the most-idle channel. When CDPD needs a data channel, it selects the least-idle channel currently not used by CDPD and not in layoff state.

If AMPS selects an idle RF channel occupied by a CDPD channel stream and the sniffer fails to switch the channel stream of the selected channel, then AMPS assumes that the selected channel is noisy and tries to find next RF channel in the idle channel pool with acceptable quality. This procedure repeats until AMPS obtains an idle RF channel, or the voice request is blocked.

In this paper, we investigate how the channel selection algorithms, the timers and other system parameters affect the performance of AMPS/CDPD systems. Specifically, based on various channel selection algorithms, we study the tradeoff between CDPD channel holding time and voice incompletion probability.

2. Input parameters and output measures

This section describes the assumptions and the output measures. We use a simulation approach to evaluate the performance of the four channel selection algorithms. Details of the simulation model are given in appendix.

The following assumptions are made in our simulation study:

- N: the number of RF channels in an AMPS BS; in our experiments, $N = 50$.
- N_CDPD: the maximum number of RF channels that can be simultaneously used by the CDPD channel streams.
- n_c: the number of active CDPD channel streams in a cell.
- n_cl: the number of idle RF channels that are either used by CDPD or in layoff state.
- n_i: the number of idle RF channels that are in the idle channel pool; in this study, “idle channels” are not used by voice users, but may be occupied by CDPD channel streams.

- n_{l}: the number of idle RF channels that are in layoff state; that is, $n_{\mathrm{l}} = n_{\mathrm{cl}} - n_{\mathrm{c}}$.
- T_{d}: the CDPD dwell time (a fixed period).
- T_{l}: the CDPD layoff time (a fixed period).
- λ: the arrival rate of new voice calls to an AMPS BS; in our experiments, the new call arrivals are a Poisson process.
- $1/\mu$: the mean voice call holding time; the voice call holding time is exponentially distributed with mean $1/\mu = 180$ s.
- $1/\eta$: the mean voice user residence time; the voice user residence times have a general distribution.
- V_{r}: the variance of the voice user residence time distribution.
- α: the probability that a forced hop is successfully performed.

For an RF channel occupied by a CDPD channel stream, if AMPS selects this channel for voice usage, then with probability α, the CDPD system successfully performs a forced hop to release this channel. The parameter α determines the effectiveness of the sniffer. A perfect sniffer can always detect the need of AMPS and $\alpha = 1$. In practice, the sniffer may not be perfect and $\alpha < 1$.

Suppose that the CDPD system is observed during a period $[0, T]$. The output measures under investigation include

- N_T: the number of voice call arrivals in $[0, T]$,
- N_{nc}: the number of incomplete voice calls in $[0, T]$,
- N_{H}: the number of channel hops occurring in $[0, T]$,
- $T_{\mathrm{CDPD}}(i)$: the amount of time that RF channel i is occupied by CDPD during $[0, T]$,
- $T_{\mathrm{CDPD}}=\sum_{i=1}^{N} T_{\mathrm{CDPD}}(i)$: the total amount of time of the RF channels used by CDPD during $[0, T]$,
- P_{nc}: the probability that a call is not completed (either blocked or forced-terminated), which is defined as

$$P_{\mathrm{nc}} = \frac{N_{\mathrm{nc}}}{N_T}, \tag{1}$$

- $E[t_{\mathrm{a}}]$: the expected CDPD channel holding time defined as

$$E[t_{\mathrm{a}}] = \frac{T_{\mathrm{CDPD}}}{N_{\mathrm{H}}}. \tag{2}$$

It is clear that the smaller the P_{nc} value, the better the performance of the AMPS system. On the other hand, the larger the $E[t_{\mathrm{a}}]$ value, the better the performance of the CDPD system.

3. Simulation results

Based on the simulation model in appendix, we conduct simulation experiments with input parameters such as the channel selection algorithm, the layoff time T_{l}, the dwell time T_{d}, the maximum number of CDPD channels N_{CDPD}, the voice user mobility rate η, the variance V_{r} of the voice user residence time distribution, and the successful forced-hop probability α. Similar results are observed in experiments with wide ranges of input values. We only present selected data. Our results indicate that η, V_{r}, α, T_{d}, T_{l}, and N_{CDPD} have the same effects on the four channel selection algorithms. Thus, except for section 3.1, we only present the results for the ML algorithm.

To simplify our discussion, the voice user residence time distribution is exponential in most of the presented results. Section 3.2 considers the effects of general residence time distribution (specifically, the Gamma distribution).

3.1. Effects of the channel selection algorithms

Figures 2 and 3 plot the voice call incompletion probability P_{nc} and the mean CDPD channel holding time $E[t_{\mathrm{a}}]$ as functions of λ under different channel selection algorithms, where $N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{d}} = 20$ s, $T_{\mathrm{l}} = 12$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 90$ s, and $\alpha = 0.1$. As shown in figure 2, it is clear that P_{nc} is an increasing function of λ. The figure indicates that when λ is small, the channel selection algorithms do not have any effect on P_{nc}. It is clear that when λ is small, AMPS can always find idle channels without being affected by CDPD.

Let “AMPS(M)” denote “AMPS exercising the most-idle channel selection algorithm”, and “AMPS(L)” denote “AMPS exercising the least-idle channel selection algorithm”. When λ is large, AMPS(L) is better than AMPS(M) in terms of P_{nc} performance for the following reason. Suppose that the channels in the idle channel pool are listed from the most-idle channel to the least-idle channel. When λ is large, the following effect is observed to explain the curves in figure 2.

Effect 1. If voice traffic is large, then (a) CDPD is more likely to occupy the least-idle channels, and (b) the layoff channels are likely to be the most-idle channels.

When voice traffic is large, it is more likely that $n_{\mathrm{c}} < N_{\mathrm{CDPD}}$ (i.e., some of the CDPD channel streams are blackout). In

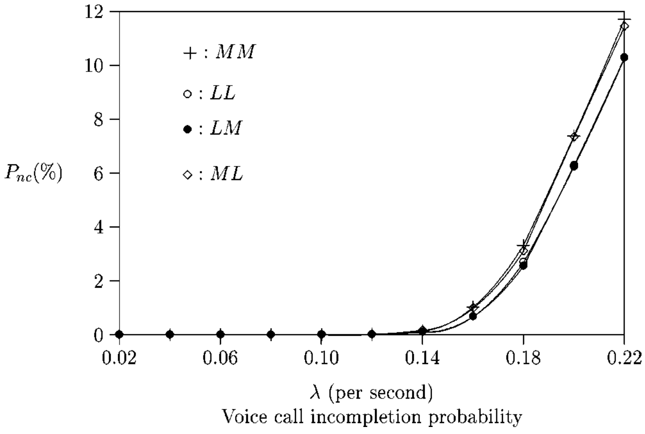


Figure 2. Effects of channel selection algorithms on AMPS ($N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{d}} = 20$ s, $T_{\mathrm{l}} = 12$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 90$ s, $\alpha = 0.1$).

this case, any RF channel c released by AMPS is immediately occupied by a blackout CDPD channel stream. Since channel c is the least-idle channel when it is returned to the idle channel pool, it implies that least-idle channels in the idle channel pool are likely to be occupied by CDPD channel streams. In this case, the layoff channels in the pool are likely to be the most-idle channels. Effect 1 holds for all CDPD channel selection algorithms considered in this paper.

If an AMPS request is satisfied when λ is large, then from effect 1(a), the selected channel is more likely to be a forced-hopped CDPD channel stream for AMPS(L), and the portion of layoff channels in the idle channel pool becomes larger. On the other hand, AMPS(M) is likely to select a layoff RF channel due to effect 1(b), and the portion of layoff channels in the idle channel pool becomes smaller. When no layoff channel exists in the idle channel pool, an AMPS request is blocked due to the channel sealing effect (with probability $1 - (1 - \alpha)^{n_c}$). For AMPS(M), the probability of no layoff idle channel is larger than that for AMPS(L). Thus, P_{nc} for AMPS(L) is smaller than that for AMPS(M).

Figure 3 plots the mean CDPD channel holding time $E[t_a]$ as a function of λ. It is intuitive that $E[t_a]$ is a decreasing function of the voice call arrival rate λ. Three effects are observed in figure 3:

Effect 2. If the idle channel pool is sufficiently large (i.e., it is likely that $n_i > n_{cl}$) and both AMPS and CDPD select idle channels from the different sides of the idle channel pool (i.e., either ML or LM is exercised), then the possibility of "collision" (i.e., AMPS selects the channel just used by CDPD) is small, and a large $E[t_a]$ is expected.

Effect 3. If both AMPS and CDPD select idle channels from the same side of the idle channel pool (i.e., either MM or LL is exercised), then it is more likely that a CDPD channel stream is interrupted when AMPS selects an idle channel.

Effect 4. If a CDPD channel stream is interrupted by AMPS due to forced hop, then the channel selected by AMPS(M) is expected to be occupied by CDPD longer than that selected by AMPS(L).

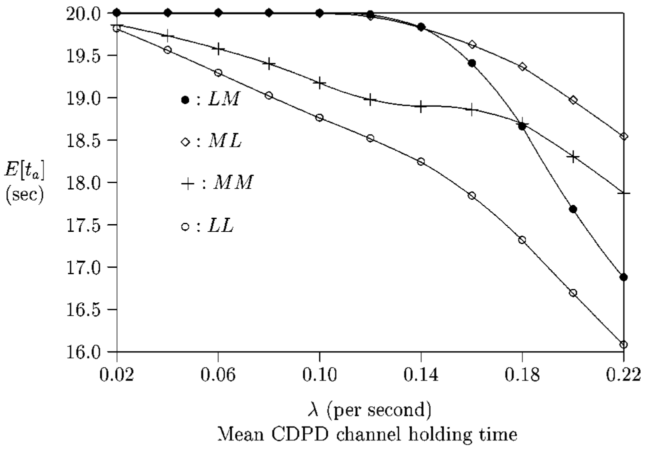


Figure 3. Effects of channel selection algorithms on CDPD ($N_{CDPD} = 10$, $T_d = 20$ s, $T_l = 12$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 90$ s, $\alpha = 0.1$).

Based on effects 1–4, we explain the phenomena observed from figure 3 in three cases. In our discussion, two relations are defined for the channel selection algorithms. The notation "=" means "same performance", and ">" means "better than".

Case I. When $\lambda \leqslant 0.14$, figure 3 indicates that ML = LM > MM > LL in terms of $E[t_a]$ performance. In this case, λ is very small, which results in a large idle channel pool ($n_i > n_{cl}$ in most cases) and effect 2 is significant. Thus, ML has similar performance as LM. ML is better than MM and LL because in this case, CDPD channel stream is unlikely to be interrupted by AMPS due to effect 2 while in MM and LL a CDPD channel stream is likely to be interrupted due to effect 3. MM is better than LL due to effect 4.

Case II. When $0.14 < \lambda \leqslant 0.18$, ML > LM > MM > LL. In this case, the AMPS traffic increases such that occasionally n_i may not be larger than n_{cl}, and it is possible that a CDPD channel stream is interrupted by AMPS. Thus, ML > LM due to effects 1 and 4. Note that effects 2 and 3 are still more significant than effects 1 and 4 (i.e., the voice traffic is not large enough to result in large number of forced hops), and the relationship LM > MM holds.

Case III. When $\lambda > 0.18$, ML > MM > LM > LL. In this case, effects 1 and 4 is more significant than effects 2 and 3, and MM > LM is expected. Due to effects 2 and 3, we have ML > MM and LM > LL.

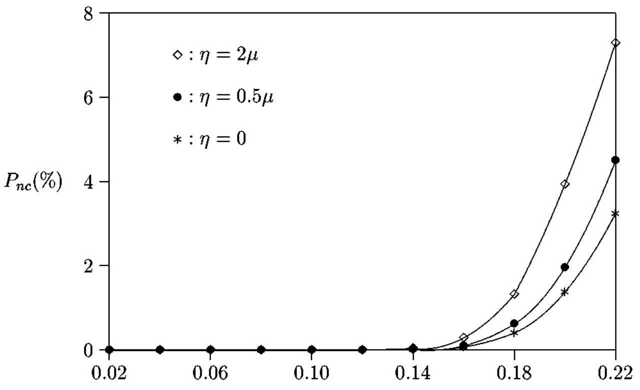
3.2. *Effects of the voice user residence time distribution*

Figure 4 plots P_{nc} and $E[t_a]$ as functions of λ for exponential voice user residence times with various voice user mobility rate η, where $N_{CDPD} = 10$, $T_d = 5$ s, $T_l = 3$ s, $1/\mu = 180$ s, $N = 50$, and $\alpha = 0.1$. The ML algorithm is considered (similar results are observed for other channel selection algorithms). It is clear that P_{nc} is an increasing function of η [6]. Figure 4(b) indicates that $E[t_a]$ is a decreasing function of η for the following reason. Increasing η increases the number of incoming handoff voice requests to a cell and thus increases the probability of forced hops, which results in degrading $E[t_a]$.

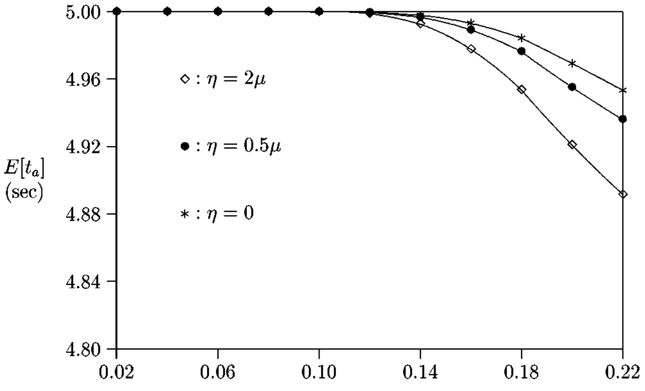
Figure 5 plots P_{nc} and $E[t_a]$ as functions of λ for Gamma voice user residence times with different variance values V_r, where $N_{CDPD} = 10$, $T_d = 5$ s, $T_l = 3$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, and $\alpha = 0.1$. Figure 5(a) indicates that P_{nc} decreases as V_r increases. This effect is insignificant when V_r is small. Figure 5(b) indicates that the effect of V_r on $E[t_a]$ is insignificant.

3.3. *Effects of the successful forced-hop probability α*

Figure 6 illustrates the impacts of α on P_{nc} and $E[t_a]$ for the ML algorithm, where $T_d = 5$ s, $T_l = 3$ s, $1/\mu = 180$ s,



(a) Voice call incompletion probability



(b) Mean CDPD channel holding time

Figure 4. Effects of η (ML with $N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{d}} = 5$ s, $T_{\mathrm{l}} = 3$ s, $1/\mu = 180$ s, $N = 50$, $\alpha = 0.1$).

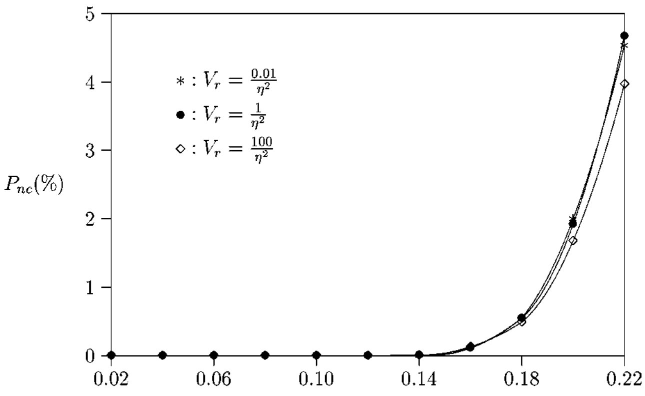
$N = 50$, $1/\eta = 360$ s, and $N_{\mathrm{CDPD}} = 10$. Figure 6 indicates that by improving the effectiveness of the sniffer, P_{nc} decreases at the cost of degrading $E[t_{\mathrm{a}}]$. We note that this effect is significant when $\alpha < 0.5$. For $\alpha > 0.5$, improving the sniffer only has insignificant effects on P_{nc} and $E[t_{\mathrm{a}}]$.

3.4. Effects of dwell time T_{d} and layoff time T_{l}

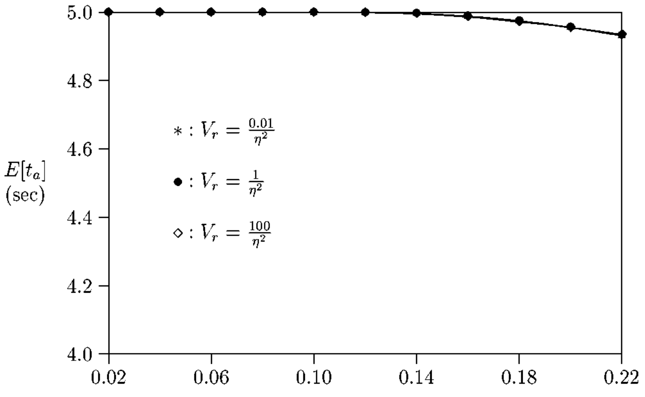
Figure 7 plots P_{nc} and $E[t_{\mathrm{a}}]$ as functions of λ for the ML algorithm with various dwell time periods T_{d}, where $N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{l}} = 3$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, and $\alpha = 0.1$. Figure 7(a) indicates the trivial result that when λ is large, P_{nc} is an increasing function of T_{d}.

It is also intuitive that $E[t_{\mathrm{a}}]$ is an increasing function of T_{d}. A nontrivial result is that $E[t_{\mathrm{a}}]$ is more sensitive to T_{d} than P_{nc} is. For example, when $\lambda = 0.22$/s, if T_{d} is increased from 5 s to 10 s, P_{nc} is increased by 35.53% and $E[t_{\mathrm{a}}]$ is increased by 95.95%.

Figure 8 plots P_{nc} and $E[t_{\mathrm{a}}]$ as functions of λ for the ML algorithm with various layoff time periods T_{l}, where $N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{d}} = 5$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, and $\alpha = 0.1$. Figure 8(a) indicates that P_{nc} decreases as T_{l} increases. Under the above selected input parameters, this effect is significant when $T_{\mathrm{l}} < 6$. Figure 8(b) indicates that T_{l} only has insignificant effect on $E[t_{\mathrm{a}}]$.



(a) Voice call incompletion probability



(b) Mean CDPD channel holding time

Figure 5. Effects of V_{r} (ML with $N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{d}} = 5$ s, $T_{\mathrm{l}} = 3$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, $\alpha = 0.1$).

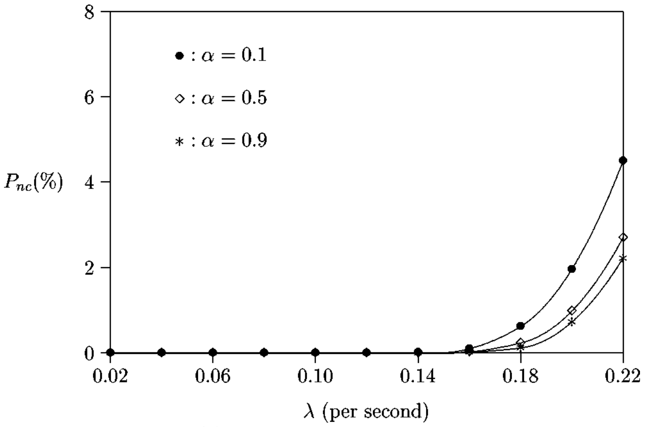
3.5. Effects of the maximum number of CDPD channels N_{CDPD}

Figure 9 illustrates the impacts of N_{CDPD} on AMPS/CDPD for the ML algorithm, where $T_{\mathrm{d}} = 5$ s, $T_{\mathrm{l}} = 3$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, and $\alpha = 0.1$. Figure 9(a) indicates that P_{nc} increases as N_{CDPD} increases. This effect is significant when $N_{\mathrm{CDPD}} < 10$, and the effect can be ignored when $N_{\mathrm{CDPD}} > 10$. For example, when $\lambda = 0.22$/s, if N_{CDPD} is increased from 5 to 10, P_{nc} is increased by 19.08%. For $N_{\mathrm{CDPD}} > 10$, if N_{CDPD} is increased from 10 to 30, P_{nc} is increased by 0.74%.

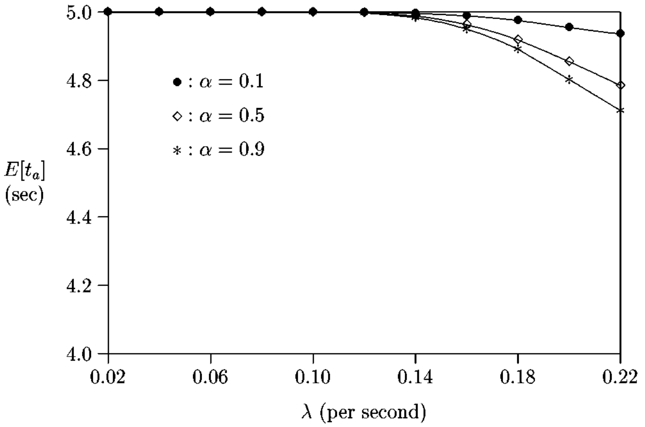
Figure 9(b) indicates that the mean CDPD channel holding time $E[t_{\mathrm{a}}]$ is a decreasing function of N_{CDPD}. However, the effect of N_{CDPD} on $E[t_{\mathrm{a}}]$ is insignificant. For example, when $\lambda = 0.22$/s, if N_{CDPD} is increased from 5 to 30, $E[t_{\mathrm{a}}]$ is decreased by only 0.86%. To conclude, increasing N_{CDPD} degrades P_{nc} without improving $E[t_{\mathrm{a}}]$ performance.

Figures 9(c) and (d) indicate that increasing N_{CDPD} increases the total number of forced hops N_{fh} and the overall CDPD system availability A_{v}^* (which is defined as N_{CDPD} multiplied by the proportion of the time that the RF channels can be used to transmit CDPD data) [4].

Based on the characteristics of the CDPD/AMPS network, different weights will be given to P_{nc}, N_{fh}, and A_{v}^*

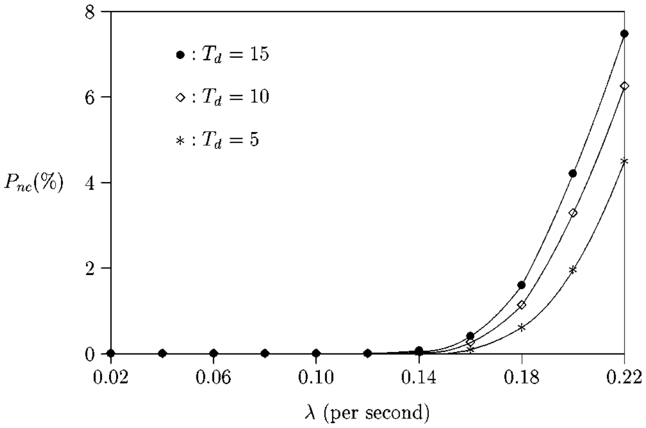


(a) Voice call incompletion probability

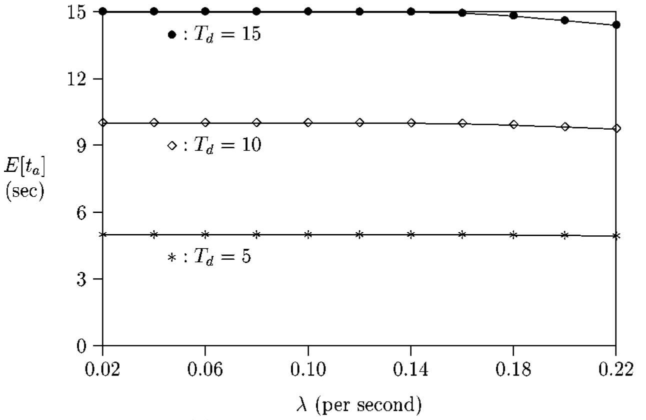


(b) Mean CDPD channel holding time

Figure 6. Effects of α (ML with $N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{d}} = 5$ s, $T_{\mathrm{l}} = 3$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s).



(a) Voice call incompletion probability



(b) Mean CDPD channel holding time

Figure 7. Effects of T_{d} (ML with $N_{\mathrm{CDPD}} = 10$, $T_{\mathrm{l}} = 3$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, $\alpha = 0.1$).

to come out a cost function. This cost function can be computed by using the results in figure 9 to determine an optimal N_{CDPD} value.

4. Conclusion

This paper studies the effects of the AMPS/CDPD channel selection algorithms, T_{d} (the dwell time), T_{l} (the layoff time), η (the voice user mobility rate), V_{r} (the variance of the voice user residence time distribution), N_{CDPD} (the maximum number of CDPD channels), and α (the successful forced-hop probability) on two output measures: P_{nc} (the voice incompletion probability) and $E[t_{\mathrm{a}}]$ (the mean CDPD channel holding time). Based on the simulation experiments, we have the following observations:

- The effects of η, V_{r}, α, T_{d}, T_{l}, and N_{CDPD} on P_{nc} and $E[t_{\mathrm{a}}]$ are similar for the four AMPS/CDPD channel selection algorithms considered in our study.
- If AMPS exercises the most-idle channel selection algorithm and CDPD exercises the least-idle channel selection algorithm, then the best $E[t_{\mathrm{a}}]$ performance is expected.
- If AMPS exercises the least-idle channel selection algorithm, then the best P_{nc} performance is expected. The CDPD channel selection algorithm does not have significant impact on P_{nc}.
- If the call arrival rate λ is sufficiently large (e.g., $\lambda > 0.14$/s in our examples), the effects of η, V_{r}, α, T_{d}, T_{l}, N_{CDPD} and the channel selection algorithms on P_{nc} are more significant.
- The effects of η, V_{r}, T_{l}, and N_{CDPD} on $E[t_{\mathrm{a}}]$ are insignificant.

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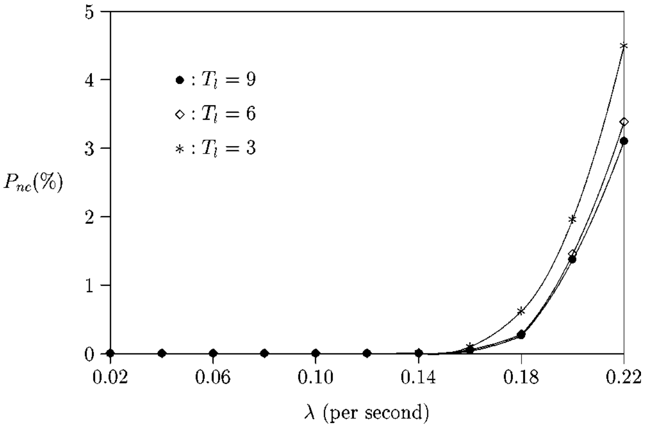
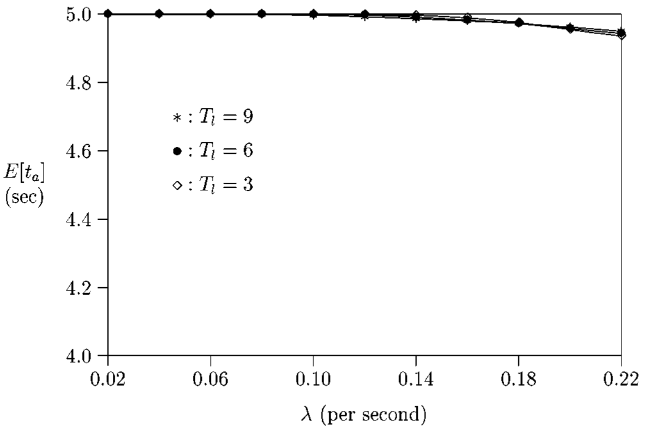
Appendix. Description of the simulation model

To simulate a very large PCS network, the MDBSs (cells) are configured in a wrapped topology. This approach eliminates the boundary effect occurs in an unwrapped topology. The mobility behavior of users in the simulation is described by a two-dimensional random walk proposed in [8]. The

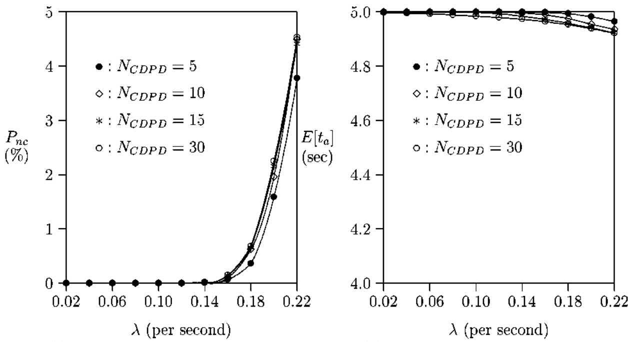


(a) The voice call incompletion probability

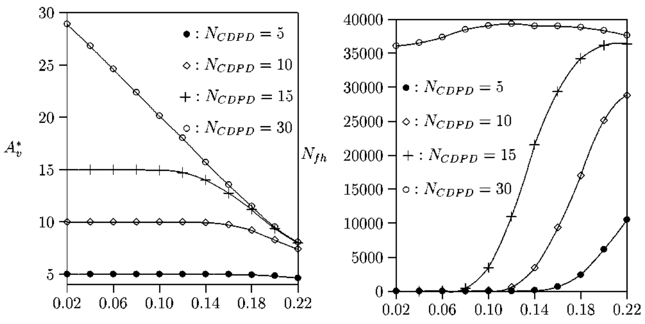


Mean CDPD channel holding time

Figure 8. Effects of T_l (ML with $N_{\mathrm{CDPD}} = 10$, $T_d = 5$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, $\alpha = 0.1$).



(a) Voice call incompletion probability (b) Mean CDPD channel holding time



(c) Overall CDPD system availability (d) Total number of forced hops

Figure 9. Effects of N_{CDPD} (ML with $T_d = 5$ s, $T_l = 3$ s, $1/\mu = 180$ s, $N = 50$, $1/\eta = 360$ s, $\alpha = 0.1$).

user moves to one of the four neighboring cells with the same routing probabilities 0.25. If the user moves from a cell to another cell before the call is completed, a handoff is performed.

We develop a discrete event simulation model to simulate the behavior of CDPD/AMPS. There are six types of events in the simulation:

- CallArrival event represents a voice call arrival.
- CallComplete event represents a voice call completion.
- TimedHop event represents the expiration of the dwell timer for an RF channel that is occupied by a CDPD channel stream.
- LayoffComplete event represents the expiration of the layoff timer for an RF channel that is not used by a CDPD channel stream.
- HandoffIn event represents a voice call in the adjacent cell exercises a handoff into this cell.
- HandoffOut event represents a voice call in this cell is handing off to the adjacent cell.

An event contains the following attributes:

- `Type` attribute indicates the type of event (CallArrival, CallComplete, TimedHop, LayoffComplete, HandoffIn, and HandoffOut).
- `Timestamp` attribute indicates the time when the event occurs.
- `ChannelNo` attribute is used in CallComplete, TimedHop, HandoffOut, or LayoffComplete events to identify the channel whose status is affected by the event.
- `CellLocation` attribute indicates the location of the cell where the event occurs.
- `CallRemain` attribute is used in HandoffIn, HandoffOut or CallArrival events to indicate the residual call holding time of the call represented by the event.

Every RF channel is characterized by a status pair. The first part is the *layoff* status, which indicates whether the channel is in the LAYOFF or the NON-LAYOFF state. The second part is the *usage* status, which indicates whether the channel is idle (the IDLE state), used by AMPS (the AMPS state), or used by a CDPD channel stream (the CDPD state). If the channel is in the LAYOFF state, then it is either idle or used by AMPS. If the channel is in the NON-LAYOFF state, then it is either idle or busy (i.e., the channel is used by an AMPS voice user or a CDPD channel stream).

A simulation clock is maintained to indicate the progress of the simulation. In other words, the clock value is the timestamp of the event being processed. The output measures of the simulation are N_{H}, N_{nc}, and T_{CDPD}, which are used to compute P_{nc} and $E[t_a]$ according to equations (1) and (2), respectively.

In every simulation run, $N_{\mathrm{T}} = 160{,}000$ incoming voice calls are simulated to ensure that the simulation results are stable. The total number of RF channels in a BS is $N = 50$. The voice call holding times are exponentially distributed

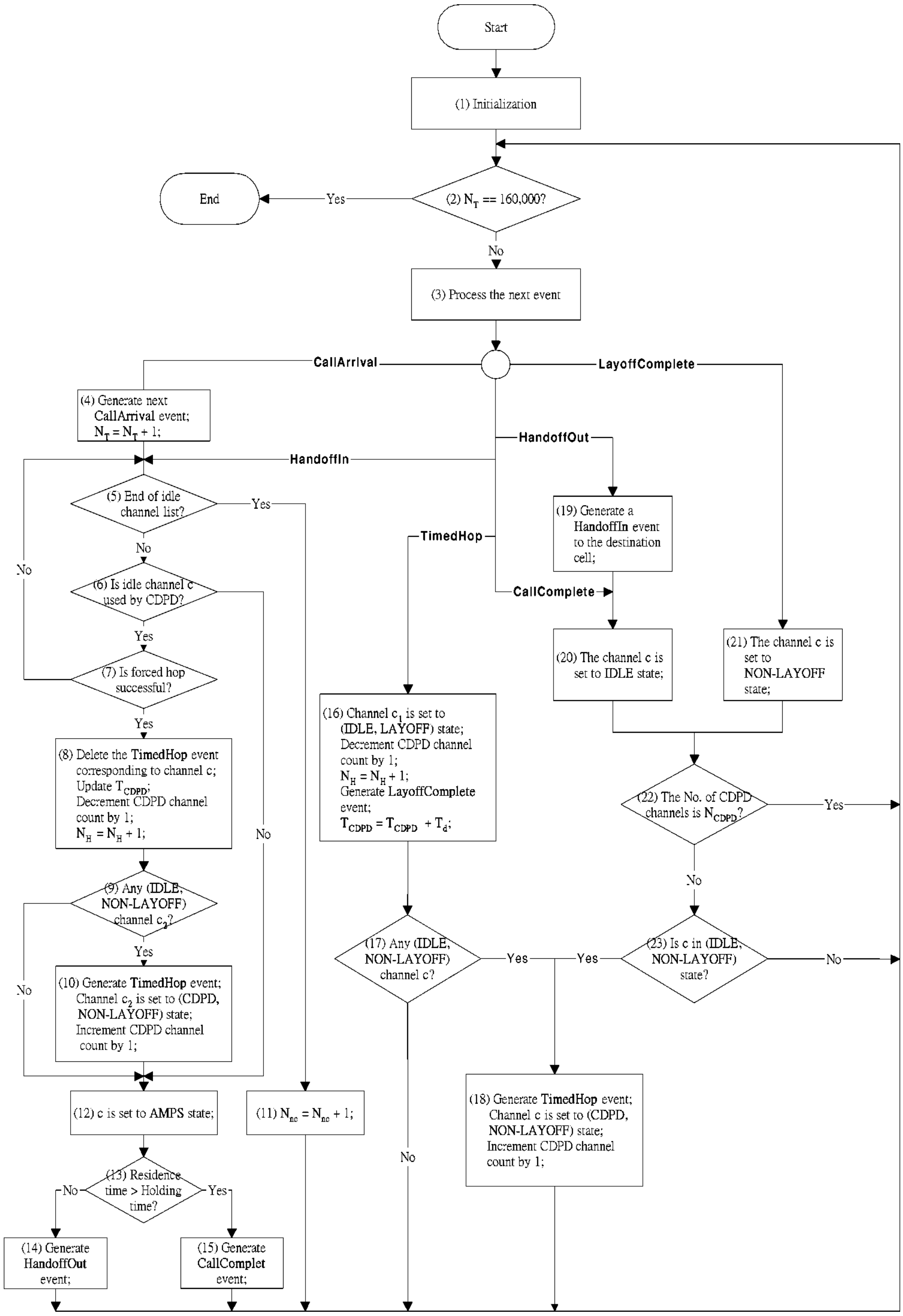


Figure 10. The simulation flow chart.

with mean $1/\mu = 180$ s, the voice user residence times have a Gamma distribution with mean $1/\eta$ s, and the voice call arrivals to the AMPS BS follow the Poisson process with rate λ. The flow chart of the simulation is given in figure 10.

Step 1 in this flow chart initializes the simulation with the following tasks:

1. Generate a CallArrival event and N_{CDPD} TimedHop events for each cell, and then insert these events into the event list. This list is sorted in the non-decreasing timestamp order.
2. For each cell, construct a double-linked list that represents the idle channel pool, set the states of N_{CDPD} RF channels as (CDPD, NON-LAYOFF), and the remaining $N - N_{\mathrm{CDPD}}$ channels as (IDLE, NON-LAYOFF).
3. Set the CDPD channel count (which represents the number of RF channels currently used by the CDPD channel streams), N_{H}, N_{T}, N_{nc}, and T_{CDPD} to 0.

Step 2 checks the number of voice call arrivals N_{T}. If N_{T} reaches 160,000, the simulation run terminates and the output measures are computed. Otherwise, step 3 is executed.

This step deletes the first event from the event list. Depending on the event type, the execution proceeds to one of the six paths (CallArrival, TimedHop, CallComplete, LayoffComplete, HandoffIn, or HandoffOut).

- The actions for the CallArrival and HandoffIn events are similar except that the CallArrival event generates the next CallArrival event in the current cell and increases N_{T} by one (see step 4). Step 5 checks if an RF channel with state IDLE or CDPD is available. If such a channel does not exist, then all RF channels are occupied by voice calls, and the voice request is blocked. In this case, N_{nc} is increased by one at step 11. Otherwise, a channel c is selected according to the voice channel selection algorithm and the state of channel c is examined at step 6. If channel c is not used by CDPD, then the state of channel c is set to AMPS at step 12. Step 13 determines whether the voice user residence time is greater than the call holding time. If so, a CallComplete event is generated at step 15. Otherwise, a HandoffOut event is generated at step 14. If channel c is used by CDPD at step 6, then step 7 checks the effectiveness of the sniffer. If forced hop to the CDPD channel stream of the selected RF channel fails, then the next idle RF channel is examined at step 5. Otherwise, step 8 deletes the TimedHop event corresponding to channel c from the event list. $T_{\mathrm{CDPD}}(c)$ is increased by the period for which the RF channel is used for CDPD until it is forced to hop. The CDPD channel count is decreased by one, and the hop count N_{H} is increased by one. Step 9 checks if an (IDLE, NON-LAYOFF) channel c_2 exists. If so, channel c_2 is set to the (CDPD, NON-LAYOFF) state, the CDPD channel count is increased by one, and a TimedHop event is generated for channel c_2 (see step 10). The `Timestamp` value of this TimedHop event is the clock value plus the dwell time T_{d}. The simulation proceeds to set the state of channel c to AMPS at step 12.
- If the event type is TimedHop, step 16 is executed where the corresponding channel c_1 (indicated by the `ChannelNo` attribute of the event) is set to the (IDLE, LAYOFF) state, the CDPD channel count is decreased by one, N_{H} is increased by one, T_{CDPD} is increased by T_{d}, and a LayoffComplete event for this RF channel is generated. The `Timestamp` value of this LayoffComplete event is the clock value plus the layoff time T_{l}. The CDPD channel stream (which releases the RF channel c_1) attempts to find another idle RF channel. Step 17 checks if an (IDLE, NON-LAYOFF) channel c exists. If so, channel c is set to the (CDPD, NON-LAYOFF) state, the CDPD channel count is increased by one, and a TimedHop event is generated for channel c (see step 18). The `Timestamp` value of this TimedHop event is the clock value plus the dwell time T_{d}.
- The actions for the CallComplete and HandoffOut events are similar except that the HandoffOut event generates a HandoffIn event to the destination cell at steps 19. The actions for the CallComplete and LayoffComplete events are similar except for the first steps (i.e., steps 20 and 21). At step 20 (i.e., the event type is CallComplete), the usage status of channel c is set to IDLE. On the other hand, step 21 (i.e., the event type is LayoffComplete) sets the layoff status of channel c as NON-LAYOFF. Steps 22 and 23 check if the number of CDPD channel streams is less than N_{CDPD} and c is in the state (IDLE, NON-LAYOFF). If so, step 18 is executed to accommodate one more CDPD channel stream by utilizing the RF channel c.

References

[1] J. Agosta and T. Russell, *CDPD: Cellular Digital Packet Data Standard and Technology* (McGraw-Hill, 1997).

[2] K.C. Budka, Cellular Digital Packet Data: Channel availability, IEEE Transactions on Vehicular Technology 46 (February 1997) 31–40.

[3] Cellular Digital Packet Data system specification: Release 1.1, CDPD Forum, Inc. (January 1995).

[4] Y.-M. Chuang, T.-Y. Lee and Y.-B. Lin, Trading CDPD availability and voice blocking probability in cellular networks, IEEE Network 12 (March/April 1998) 48–54.

[5] W.C.Y. Lee, *Mobile Cellular Telecommunications Systems* (McGraw-Hill, 1995).

[6] Y.-B. Lin, Modeling techniques for large-scale PCS networks, IEEE Communications Magazine 35 (February 1997) 102–107.

[7] Y.-B. Lin and Y.-M. Chuang, Modeling the sleep mode for Cellular Digital Packet Data, IEEE Communications Letters 3 (March 1999) 63–65.

[8] Y.-B. Lin and P. Fishwick, Asynchronous parallel discrete event simulation, IEEE Transactions on Systems, Man, and Cybernetics 26 (1996) 397–412.

[9] R.F. Quick Jr., An overview of the Cellular Digital Packet Data (CDPD) system, in: *Proc. IEEE Personal Indoor And Mobile Radio Conference* (1993) pp. 338–343.

[10] M. Sreetharan and R. Kumar, *Cellular Digital Packet Data* (Artech House, 1996).

[11] M. Taylor, W. Waung and M. Banan, *Internetwork Mobility, The CDPD Approach* (Prentice Hall, 1997).

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