# A Throughput Model for CSMA/CA with a Cross-Layer Payload-Dropping Optimization

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***Abstract*— In this paper, we formulate the throughput of a spatially-optimized CSMA/CA in two interference-limited co-channel cells, and validate it using statistics obtained via simulation. This special variant of the protocol incorporates a MAC/PHY cross-layer mechanism which aborts the reception of the payload portions of frames from co-channel cells in interference-limited multi-cell deployments. For physical transceivers relying solely on preamble detection for carrier sensing, this optimization adequately mitigates the exposed node syndrome, thereby allowing nodes to enjoy nearly the maximum throughput as provided by CSMA/CA in single cell or carrier-sensing threshold (CST) isolated scenarios.**

***Index Terms*— CSMA/CA, MAC/PHY cross-layer design, spatial reuse, multi-cell wireless LANs, throughput model.**

## I. Introduction

CSMA/CA [1,2] uses clear channel assessment (CCA) in the physical layer (PHY) to detect whether the channel is busy with transmissions. After a busy period, a node with a new frame to transmit initializes a counter to a value $w$ polled randomly from within a fixed range. The node proceeds to perform CCA at each slot, decrementing this counter if the channel is idle. When the counter reaches zero, the node transmits at the next slot. If the channel is busy, the counting process is suspended until it is idle again (Fig.1(a)).

CCA may be implemented using one or both of the following methods: preamble and energy detection. The former is the simplest because it is by itself a required circuitry in PHY. The latter requires additional circuitry, but provides a carrier sensing threshold (CST) with which weak signals may be prevented from being detected to some extent, thereby allowing co-channel, interference-limited cells to behave as if in isolation [3-5] (Fig.1(a)). However, CST is not so straight forward in wideband systems, and also negatively affects the frame detection rate [6]. For simplicity and robustness sake, implementers may opt for the former. In this case, CSMA/CA would exhibit the exposed node syndrome: transmissions in one cell would cause nodes in another cell to detect the channel as busy and needlessly wait for the transmission to end before resuming their contention process (Fig.1(b)). To avoid this scenario, different preamble patterns may be used for each cell [7], provided there are enough orthogonal preamble patterns. Alternatively, we could use the following scheme: let CCA indicate the channel as busy when the preamble and header is detected, but remove the indication and stop the frame reception process if signal measurements and/or information obtained during the preamble/header processing stage suggests that the frame is from outside the interference range of the node's cell [8,9]. This allows the CSMA/CA protocol to resume its backoff during the time that would have otherwise been spent receiving the frame's payload (Fig.1(c)). We call this cross-layer optimized variant of CSMA/CA the Payload-Dropping CSMA/CA (PD-CSMA/CA).

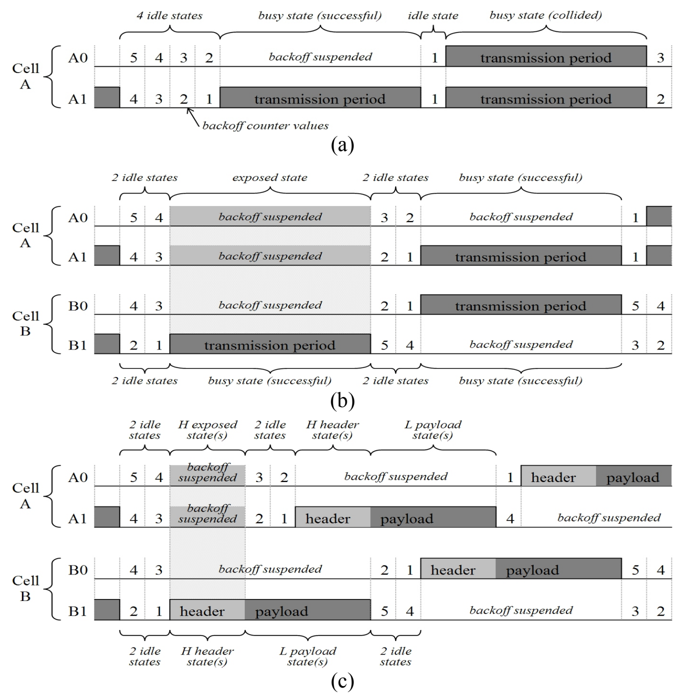


Fig.1: Transmission patterns of CSMA/CA nodes: (a) in an isolated cell, (b) in two exposed cells, and (c) with payload-dropping optimization.

## II. Related Work

As starting points, we use Bianchi's Markov chain analysis method [10] and Hu et al.'s corrected channel state model [11] for the isolated cell scenario. In the multi-cell scenario, we studied Garcia et al.'s approach of using frame outage for the effects of co-channel interferences in large networks [12] and Bonard's scheme of dividing multi-cell area into regions which are blocked when neighbouring regions are transmitting [13], but did not find any slot-by-slot modelling ideas that we could use. For ideas we could use, Panda et al.'s throughput model of two IEEE 802.11 cells outside of error-free reception range, yet within sensing range [13], and Chong et al.'s single

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cell cross-layer model, which took into consideration false detection scenarios which cause frame transmissions to stagger [15] were most promising. We started our work based on the former, but had to discard it because it could not deal with transmissions that stagger rather than just coincident. We also considered modelling the exposed states (Fig.1(c)) as false detection events as per the latter paper. Unfortunately, the false detection probability is an input into the system in [15], whereas in ours, it is an internal characteristic dependent only on the preamble/header, payload and the contention window lengths. Furthermore, a special coupling effect occurs between the cells during the exposed slots: due to the offset introduced, exposure in subsequent idle periods become less likely. For long periods of time, transmissions alternately stagger one after another in succession, as if the cells were in isolation.

## III. SYSTEM MODEL

The two-cell topology is adopted. These two cells are in carrier sensing range. In between them, other cells maybe operating in different channels with negligible crosstalk and is thus ignored in our analysis. Each cell serves $N$ number of nodes ranging between 2 to 10, and are sized and spaced at an interference-limiting distance, i.e., such that even if all nodes in one cell were to transmit concurrently, the power of the cumulative interference would not be enough to corrupt a singular transmission occurring at the same time between any two nodes in the other cell.

There are no transmissions between cells. Within each cell, the transmissions are assumed to be single-hop peer to peer as in ad hoc networks. As in [10,11,13,15], each node operates at saturation load. Singular transmissions in a cell are received error-free regardless of the number of ongoing transmissions in the other cell (since the cells are interference-limited). For collided transmissions, the payload is assumed corrupted, but information encoded, derivable or measurable from the PHY preamble and header survives for the node to determine whether the transmitter of the captured signal is in the same cell. To this end, it is assumed a low modulation rate, a high level spreading and redundancy in coding the PHY header. There is strong evidence that this is plausible for headers designed thus, owing to delay and power capture [16], especially for the small number of nodes and collisions. In the case that it is not, our throughput hypothesis will still be useful as a theoretical upper-bound that PD-CSMA/CA can deliver.

Each busy period whether collided or successful consists of a header period, $H$, and payload period, $P$, that are both rounded up to and expressed as an integral multiple of the contention slot duration, $\sigma$. This assumption makes our model more suitable for baseline CSMA/CA as per analyses done in [2,15], where it is assumed the acknowledgement mechanism is conveyed in another channel, or where its transmission time is negligible compared to that of the payload frame. In the latter case, the preamble for the acknowledgment frame is assumed to be encoded using pattern different from that used for the payload, as exposure to additional frame headers within the busy period is not accounted by the model.

The contention window, $CW$, is assumed to be fixed, as in [15], and always shorter than the payload duration, $P$.

## IV. THROUGHPUT ANALYSIS FOR PD-CSMA/CA

### A. Isolated Cell Throughput

Our analysis depends on formulations for the isolated cell scenario. Let $C \in [0, N]$ represent the number of transmissions at the start of each idle slot or busy period in the isolated cell. With a fixed contention window, C's transition probabilities for a single isolated cell can be worked out from [11] as:

$$p_{CT}(j,i) = \begin{cases} \binom{N}{j}\left(\frac{2}{CW}\right)^{j}\left(\frac{CW-2}{CW}\right)^{N-j} & i=0, \quad j\in[0,N] \\ \binom{i}{j}\left(\frac{1}{CW}\right)^{j}\left(\frac{CW-1}{CW}\right)^{i-j} & i\in[1,N], \quad j\in[0,i] \\ 0 & i\in[1,N], \quad j\in[i+1,N] \end{cases} \tag{1}$$

Here, $p_{CT}(j, i) \equiv \Pr[C_{t+1} = j \mid C_t = i]$ with $i$ and $j$ being the value of the current and next channel states, respectively. $N$ denotes the total number of nodes in the cell and $CW$, the contention window length. $p_{CT}(j, i)$ forms the elements of a state transition matrix which completes the equilibrium equations for the Markov chain for $C$:

$$\begin{cases} \begin{bmatrix} p_C(0) \\ p_C(1) \\ \vdots \\ p_C(N) \end{bmatrix} = \begin{bmatrix} p_{CT}(0,0) & p_{CT}(0,1) & \cdots & p_{CT}(0,N) \\ p_{CT}(1,0) & p_{CT}(1,1) & \cdots & p_{CT}(1,N) \\ \vdots & \vdots & \ddots & \vdots \\ p_{CT}(N,0) & p_{CT}(N,0) & \cdots & p_{CT}(N,N) \end{bmatrix} \begin{bmatrix} p_C(0) \\ p_C(1) \\ \vdots \\ p_C(N) \end{bmatrix} \\ \sum_{c=0}^{N} p_C(c) = 1 \end{cases} \tag{2}$$

$p_C(i) \equiv \Pr[C = i]$, i.e., the rate at which the state ($C = i$) occurs after an infinitely long run of the system, can be determined using Matlab or a recursive C program as follows:

$$\begin{bmatrix} p_C(0) \\ p_C(1) \\ \vdots \\ p_C(N) \end{bmatrix} = \lim_{n\to\infty} \begin{bmatrix} p_{CT}(0,0) & p_{CT}(0,1) & \cdots & p_{CT}(0,N) \\ p_{CT}(1,0) & p_{CT}(1,1) & \cdots & p_{CT}(1,N) \\ \vdots & \vdots & \ddots & \vdots \\ p_{CT}(N,0) & p_{CT}(N,0) & \cdots & p_{CT}(N,N) \end{bmatrix}^{n} \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

With $p_C(i)$, the normalized throughput of a single, isolated CSMA/CA cell with $N$ nodes can be expressed as [10]:

$$\eta_{iso} = \frac{P \cdot p_C(1)}{\sigma \cdot p_C(0) + T_s \cdot p_C(1) + T_c \cdot \sum_{c=2}^{N} p_C(c)} \tag{4}$$

Here, $P$ is the length of time spent in transmitting the payload during each busy state, while $\sigma$, $T_s$ and $T_c$ are the durations of the idle slot ($C = 0$), successful state ($C = 1$) and collided state ($C \in [2, N]$), respectively. The actual throughput for the cell can be obtained by multiplying $\eta_{iso}$ with PHY's data transmission rate. Let $L$ represent the duration of the busy period ($L = H + P$). Since we assume that the duration of the collided busy period approximates that of the successful state ($T_c \approx T_s$), and that the header and payload periods are both rounded up to and expressed as an integral multiple of the idle slot duration, Eq.(4) simplifies to:

$$\eta_{iso} = \frac{P \cdot p_C(1)}{p_C(0) + L \cdot (1 - p_C(0))} \tag{5}$$

*B. PD-CSMA/CA System States*

A study of PD-CSMA/CA's transmission pattern reveals two properties: Firstly, the overlap of the $t$-th and ($t$+1)-th busy periods is largely dependent on the degree of overlap of the ($t$-1)-th and $t$-th staggered pair and the length of idle period following the $t$-th transmission. Secondly, if the exposed slots in the transmission pattern of one cell were removed, the resulting pattern would be exactly that of a cell in isolation. If we know its rate of occurrence, we can easily account for it by adding extra idle slots into the single cell throughput formula. Based on these two observations, intuitively, we take the system state as comprising a staggered pair of busy periods and the exposed slots preceding it. We represent these states as $S_{o,e}$, where $o \in [1, L]$ is the overlap measured in slots, while $e \in [0, H]$ is the number of preceding exposed slots.

Let $p_I(i) \equiv \Pr[I = i]$ where $i \in [0, CW]$ denote the distribution of the idle period in the single cell scenario. We can approximate this distribution as follows:

$$p_I(i) = \begin{cases} \dfrac{\sum_{c=1}^{N}\left[p_C(c) \cdot \sum_{c'=1}^{c} p_{CT}(c', c)\right]}{\sum_{c=1}^{N} p_C(c)} & i = 0 \\[2ex] \dfrac{\sum_{c=1}^{N}\left[p_C(c) \cdot p_{CT}(0, c)\right] \times p_{CT}(0,0)^{i-1} \cdot \sum_{c=1}^{N} p_{CT}(c, 0)}{\sum_{c=1}^{N} p_C(c)} & i \in [1, CW-1] \end{cases} \tag{6}$$

The first clause in the formula is simply the probability that a busy period is immediately followed by another. The second clause is the probability of a string of idle states of length $i$ occurring after a busy period.

In PD-CSMA/CA the statistics of the idle periods preceding two or more consecutive transmissions in a cell, or those preceding the staggered transmissions in the two cells, are unlikely to follow $p_I(i)$, since the stagger patterns would temporarily straddle them to some fixed combinations of lengths. However, we make this simplifying assumption in order to approximate the system state as a Markov chain.

*C. System State Transition Probabilities*

The space for the system state comprises 4 main categories as shown in Fig. 2. A study of these four ranges of overlap and the permutations of the durations of the idle periods following them allows us to completely define the transition probabilities, $p_{ST}(S_{o(t+1),e(t+1)}, S_{o(t),e(t)}) \equiv \Pr[S_{o(t+1),e(t+1)} \mid S_{o(t),e(t)}]$ for the system state's Markov chain approximation (Eqs.(7)-(14)). We adopt the symbol names in Fig. 2 in so doing:

*1) o = L.* As shown in Fig. 2(a), this is the state where the busy periods in the two cells, $b_A(t)$ and $b_B(t)$ are exactly coincident. If following this, the next idle periods $i_A(t+1)$ and $i_B(t+1)$ are also of equal duration, the following state will also

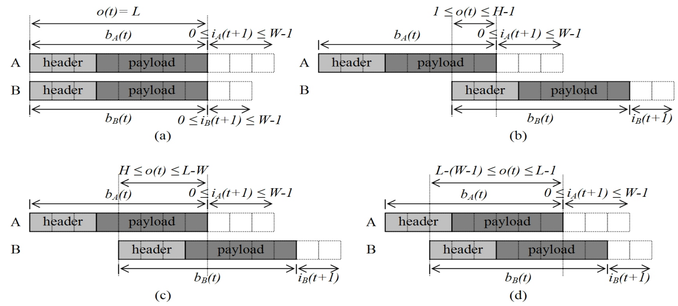



Fig. 2: The general system state categories

have coincident busy periods. Since these new busy periods are coincident, neither cell will suffer exposed slots. The probability for this to occur is:

$$p_{ST}(S_{L,0}, S_{L,0}) = \sum_{i=0}^{CW-1} p_I(i)^2 \tag{7}$$

If the durations of $i_A(t+1)$ and $i_B(t+1)$ differ by $x$, the subsequent busy periods will overlap by ($P$ - $x$) slots. Since one cell will be sensing while the other starts its busy period, $H$ exposed slots will be encountered by the cell with the longer idle period. The transition probabilities to these new states are:

$$p_{ST}(S_{P-x,H}, S_{L,0}) = 2 \cdot \sum_{i=x}^{CW-1} p_I(i) \cdot p_I(i-x) \quad x \in [1, CW-1] \tag{8}$$

A factor of two is included in the expression since the symmetrical condition allows for the next busy periods to be staggered either left or right.

*2) o ∈ [1, H - 1].* These are the cases where the overlap width of the busy periods is shorter than the header period (Fig. 2(b)). If subsequently, cell A's idle period $i_A(t+1)$ equals 0, the next system state will be that of cell A's ($t$+1)-th busy period $b_A(t+1)$ overlapping $b_B(t)$ by ($L$-$o$) slots. Because $b_A(t+1)$ immediately follows $b_A(t)$, cell A will not have exposed slots in these new states:

$$p_{ST}(S_{L-o,0}, S_{o,e}) = p_I(0) \quad o \in [1, H-1],\ e \in [0, H] \tag{9}$$

Let $x$ be the duration of $i_A(t+1)$. If $x$ is not zero, then cell A will be exposed for the remainder of the header transmission period in cell B. Subsequently, the next system state will have $b_A(t+1)$ overlapped with $b_B(t)$ by ($P$ - $x$). The probabilities for this set of transitions are:

$$p_{ST}(S_{P-x,H-o}, S_{o,e}) = p_I(x) \quad o \in [1, H-1],\ e \in [0, H] \quad x \in [1, CW-1] \tag{10}$$

*3) o ∈ [H, L - CW].* In these system states, $b_A(t)$ fully overlaps the header period in $b_B(t)$, so that it is not possible for the next busy state in cell A to be preceded by exposed slots Fig. 2(c). Also, since the remainder part of $b_B(t)$ that is not overlapped with $b_A(t)$ is longer than maximum idle period (C$W$ - 1), the next state will be that of $b_A(t+1)$ overlapping with $b_B(t)$ by ($L$ - $o$ - $x$), where $x$ is the duration of $i_A(t+1)$:

$$p_{ST}(S_{L-o-x,0}, S_{o,e}) = p_I(x) \quad o \in [H, L-CW],\ e \in [0, H] \quad x \in [0, CW-1] \tag{11}$$

*4)* $o \in [L - (CW - 1), L - 1]$. In these system states, $b_A(t)$ and $b_B(t)$ are overlapped such that the following idle period in cell A, $i_A(t+1)$, have a chance to extend beyond $b_B(t)$ (Fig. 2(d)). If $i_A(t+1)$ does not extend beyond $b_B(t)$, i.e., its duration $x$ is within $[0, L - o - 1]$, then the next system states will have $b_A(t+1)$ and $b_B(t)$ overlapped by $(L - o - x)$:

$$p_{ST}\left(S_{L-o-x,0}, S_{o,e}\right) = p_I(x) \quad o \in [L-(CW-1), L-1], \quad e \in [0,H], \quad x \in [0, L-o-1] \tag{12}$$

If however $i_A(t+1)$ ends with or goes beyond $b_B(t)$, i.e., $i_A(t+1) \in [L - o, CW - 1]$, a coincident busy period would occur next if $i_B(t+1)$ and the part of $i_A(t+1)$ extending beyond $b_B(t)$ are equal in duration, i.e., $i_B(t+1) = i_A(t+1) - (L - o)$:

$$p_{ST}\left(S_{L,0}, S_{o,e}\right) = \sum_{i=L-o}^{CW-1} p_I(i) \cdot p_I(i-(L-o)) \quad o \in [L-(CW-1), L-1], \quad e \in [0,H] \tag{13}$$

If $i_B(t+1)$ is longer than the part of $i_A(t+1)$ extending beyond $b_B(t)$ by x, i.e., $i_B(t+1) = i_A(t+1) - (L - o) + x$, the next system state will have $b_A(t+1)$ staggered left of $b_B(t+1)$ with an overlap of $(P - x)$. Conversely, if the part of $i_A(t+1)$ extending beyond $b_B(t)$ is longer by $i_B(t+1)$ by the same amount of $x$, i.e., $i_A(t+1) - (L - o) = i_B(t+1) + x$, then the following system state will have its busy periods staggered to the right but with the same overlap of $(P - x)$. Since we do not make a distinction between a left stagger and a right stagger in our system state definition, the transition probabilities are combined as follows:

$$p_{ST}\left(S_{P-x,H}, S_{o,e}\right) = \begin{cases} \displaystyle\sum_{i=L-o}^{CW-1-(L-o)-x} p_I(i) \cdot p_I(i-(L-o)+x) + \sum_{i=L-o+x}^{CW-1} p_I(i) \cdot p_I(i-(L-o)-x) & x \in [1, CW-1-(L-o)] \\ \displaystyle\sum_{i=L-o}^{CW-1-(L-o)-x} p_I(i) \cdot p_I(i-(L-o)+x) & x \in [CW-1-(L-o)+1, CW-1] \end{cases} \quad o \in [L-(CW-1), L-1], \quad e \in [0,H] \tag{14}$$

$p_S(S_{o,e}) \equiv \Pr[S = S_{o,e}]$, i.e., the rate or probability with which a particular system state occurs after an infinitely long run of the system, can be determined similarly as Eq.(3).

### *D. PD-CSMA/CA Throughput*

Denote $\varepsilon$ as the occurrence rate of the exposed slot compared to the occurrence rate of a busy period. From the PD-CSMA/CA system state probabilities $p_S(S_{o,e})$, we can determine the value of this coefficient in one of the cells as follows:

$$\varepsilon = \frac{\frac{1}{2} \cdot \sum_{e=1}^{H} \sum_{o=1}^{L-1} e \cdot p_S(S_{o,e})}{p_S(S_{L,0}) + \sum_{o=P-1}^{L-1} p_S(S_{o,H}) + \frac{1}{2} \cdot \sum_{e=0}^{H} \sum_{o=1}^{L-1} p_S(S_{o,e})} \tag{15}$$

The numerator in the equation above gives the expectation for the number of exposed slots per system state. A factor of half is applied to it since the exposed slots given by the system state is for two cells. The denominator yields the expectation of the number of busy periods per system state. The factor of half applied to the last term in the denominator is to account for the fact that in a system state $S_{o,e}$ with $e \in [0, H - 1]$ and $o \in [1, L - 1]$, the lagging busy period is in fact the leading busy period in the previous system state. In this case, each new system state just adds one more busy period, or half if only one cell is considered (as is the case at hand).

With this exposed slot factor, we can now modify the single cell throughput formula in Eq.(5) to yield the throughput of one cell in the payload dropping scenario as follows:

$$\eta_{pd} = \frac{P.p_C(1)}{p_C(0) + (\varepsilon + L) \cdot (1 - p_C(0))} \tag{16}$$

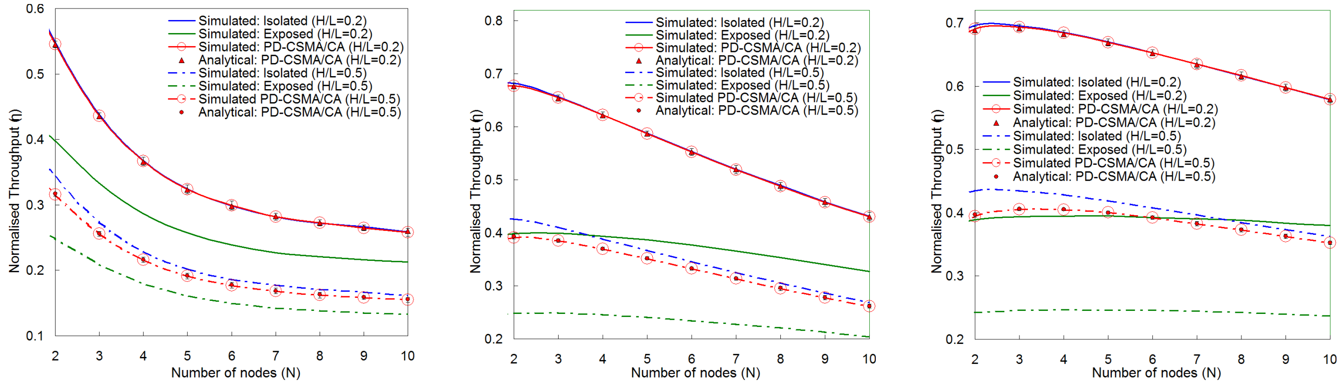
Note that the added term in the denominator represents the loss of channel time due to the exposed slots.

## V. Validation

We used the ns-2 simulator [17] to test our model. Table 1 shows the parameters we used. Broadcast frames were used so that the busy periods for successful or collided transmissions have the same duration. To simulate payload dropping, the C code was modified so that reception is aborted and the channel declared idle if the cumulative signal level is under the reception threshold. Figs. 3-4 present our results. In each setting, the analytical value for the PD-CSMA/CA throughput falls within the 95% confidence interval of the 30 samples obtained. On these result, we can make some observations: For the *H/L* ratio of 0.2, the throughput of PD-CSMA/CA is almost that of the isolated scenario. This is due to the effect where, whenever a cell experiences exposed slots during an idle period, its idle period is started in the other cell's busy period. Subsequently the chance of experiencing exposed slots is reduced. As the *H/L* ratio increases, PD-CSMA/CA approaches the exposed throughput, since the time spent being exposed gets larger as the header length is longer. Also, the gap between PD-CSMA/CA and isolated throughput is bigger for smaller number of nodes, due to increased chance of exposed slots in the longer idle periods.

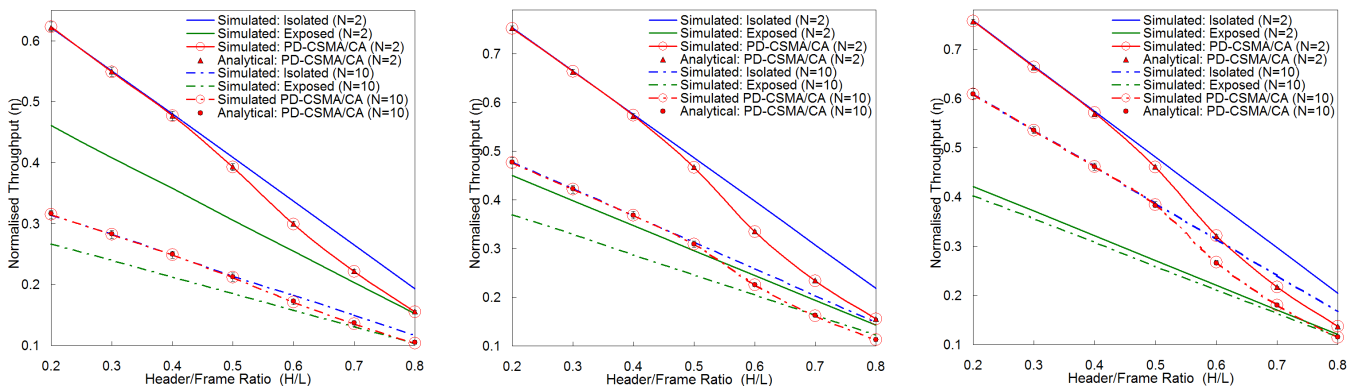
TABLE I
SIMULATION SETTINGS

| Parameter | Value(s) |
|---|---|
| Propagation index (n) | 4 |
| Reference signal level at 1m (Pt) | 20 dBm |
| Carrier sensing threshold (CSThresh) | -95 dBm |
| Reception threshold (RXThresh) | -30 dBm |
| Capture threshold (α) | 20 dBm |
| Cell diameter (2R) | 10 m |
| Cell distance (D) | 100 m |
| Minimum proximity of nodes in each cell | 1 m |
| Idle slot duration (σ) | 20 µs |
| Number of nodes per cell (N) | {2,3,..10} |
| Contention window length (CW) | {4,16,32} σ |
| Frame duration (L = H+P) | {10,20,40,70,80,160} σ |
| Header/Frame Ratio (H/L) | {0.2, 0.3, ..0.8} |
| Simulation duration | 5000 busy periods |
| Runs per setting | 30 |




(a) (b) (c)

Fig. 3: PD-CSMA/CA throughput versus number of nodes for $H/L = \{0.2, 0.5\}$ and a) $CW$=4, $L$=10 b) $CW$=16, $L$=40 c) $CW$=32, $L$=70




(a) (b) (c)

Fig. 4: PD-CSMA/CA throughput versus header/payload ratio for $N = \{2, 10\}$, and a) $CW$=4, $L$=20 b) $CW$=16, $L$=80 c) $CW$=32, $L$=160

## VI. Conclusion

We developed a two-cell model for analysing CSMA/CA with a cross-layer payload dropping mechanism to improve throughput in interference-limited cells. We defined a system state for this model, approximated and solved its steady state distribution via Markov chain analysis. We then derived and verified its throughput via simulation. Our model, though limited to just two-cell, serves to provide some analytical throughput insights on this special variant of CSMA/CA.

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