COMPARISON OF CONTENTION-BASED PROTOCOLS FOR SECONDARY ACCESS IN TV WHITESPACES

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ABSTRACT

The performance of the contention-based protocols in 802.11 and ECMA-392 are described and analyzed. Their suitability for various scenarios in TV whitespaces are evaluated. We demonstrate that by adjusting a single parameter over a limited range of values, a high throughput can be maintained. At the same time we can limit the effects of aggregate interference (where multiple secondary stations transmit on the channel at the same time), which could potentially cause interference to primary systems. We describe how the backoff behaviour of both protocols can be compared and evaluated using Markov chains. A description of an extremely fast and efficient way to solve these large and complex chains is given.

1. INTRODUCTION

TV whitespaces (TVWS) refer to one of the spectrum bands that are early candidates for dynamic spectrum access (DSA). DSA improves spectral efficiency by allowing for unlicensed/secondary users to opportunistically access spectrum while protecting licensed/primary users. In the case of TVWS the primary users can be TV broadcasters and wireless microphones.

Regulatory approval of TVWS is progressing rapidly. In the USA, the FCC has released a document which determines the final rules for the use of TVWS [1]. These new rules remove mandatory sensing requirements, thus facilitating the use of geolocation-based channel allocation. In the UK, Ofcom is consulting on a draft Statutory Instrument to make whitespace devices licence-exempt. Ofcom also plans to work with stakeholders to make information about existing licensed services that operate in the TV band available to prospective database providers, and expects that TVWS technology could be launched in the UK in 2013 [2].

While primary systems are protected from interference from secondary systems, secondary systems themselves must be able to coexist with one another; however, the rules and etiquette methods to allow for this are still being developed. Contention-based protocols using random backoff mechanisms are therefore attractive for users, especially early adopters, of TVWS due to the ease of coexistence with other systems. This can be seen from the success of contention-based access in other shared spectrum such as the 2.4GHz ISM band. The ECMA-392 standard [3] is already released and defines TVWS channel access mechanisms including prioritized channel access (PCA) for contention-based channel access. The 802.11 standard [4] can provide prioritized contention-based access using enhanced distributed channel access (EDCA). IEEE 802.11 task group AF are currently developing the modifications to this standard to allow for co-existence in TVWS. It is expected that 802.11af will include a contention-based mechanism with similar behaviour to EDCA. Test-bed implementations of ECMA-392 and 802.11 in TVWS are already available as shown in [5] and [6] respectively which suggests both could be early adopters of TVWS.

There are many potential scenarios that could benefit from opportunistic channel access; examples are provided in [7] and [8]. Currently there is a focus towards opportunistic channel access in TVWS as this band is becoming available in the near future, but also because of the favourable propagation characteristics of the TV band. This allows for relatively good coverage using relatively low transmit powers. Example scenarios that could use TVWS include home networking and indoor-to-outdoor coverage. Indoor-to-outdoor coverage describes the coverage of users on streets from access points within buildings.

In this paper the behaviour and performance of the backoff mechanisms of the 802.11 and ECMA-392 protocols are compared. Although the backoff mechanisms are similar there is a key difference in the way that contention window values are reset which can cause significantly different performance. Based on the performance results the suitability of each of these protocols is judged for different deployment scenarios. The performance of these backoff schemes is analyzed using Markov chain analysis. These sorts of Markov chains can be extremely large and difficult to solve so a description is provided in this paper of a highly efficient way to solve Markov chains which could be used for more complex systems than shown here.

Parameter adjustments are also investigated in this paper to show how high throughputs can be maintained and how aggregate interference can be kept low. Aggregate interference must not exceed the interference thresholds of any primary users. The number of simultaneous transmissions from secondary systems should therefore be limited to avoid these issues. The solution to aggregate interference may also involve further mechanisms such as power control, an example of which is described in [9], to make sure that secondary systems do not interfere with the primary users.

This is the first paper to give a detailed comparison of the behaviours of the 802.11 and ECMA-392 contention-based mechanisms. This is motivated by feedback from discussions which the authors have had following presentations which gave only a brief comparison of these issues [10], [11].

This paper is organized as follows. Section 2 provides an overview of both the 802.11 EDCA and ECMA-392 PCA access mechanisms while section 3 describes the Markov chains used and how to solve them. Results are provided and discussed in section 5 followed by conclusions in section 6.

2. PROTOCOL OVERVIEWS

Both 802.11 EDCA and ECMA-392 PCA use carrier-sense multiple access with collision avoidance (CSMA/CA) for contention-based access. First a description is provided for EDCA followed by the description for PCA. The performance of the two protocols is then compared.

When a packet arrives at an 802.11 EDCA station it is mapped into one of four access categories (AC). Each AC contends for the channel using its own channel access function (CAF). Each CAF has its own parameter set which includes CW_{min}, CW_{max}, *AIFSN* and $TXOP_{\text{limit}}$. When a packet first arrives at a CAF, the CAF will first sense the channel. If the channel is sensed idle for an arbitration interframe space (AIFS), which is one short interframe space (SIFS) plus *AIFSN* timeslots, then the packet will be transmitted. If, however, the channel is initially sensed busy, or becomes busy during AIFS, then the backoff procedure is invoked. The CAF will have a contention window (CW) with a value of *CW*. Initially CW is set to CW_{min}. A random backoff time is then selected from the range [0,*CW*]. After the CAF senses the channel to be idle for a duration of AIFS, the system will countdown its backoff for each idle timeslot. If the channel becomes busy the backoff will freeze and will continue again once the channel has been idle for a further AIFS duration. Once the backoff counter has reached zero, the CAF can transmit the packet. If more than one CAF at the same station attempt to transmit at the same time then the highest priority of those CAFs is allowed to transmit on the channel while the other CAFs assume failed transmissions due to this internal collision. If the intended recipient station successfully receives a transmitted packet then it will send an acknowledgement back to the sender station following a SIFS interval. If an acknowledgement is not received the sender station assumes that its transmission was unsuccessful. Following an unsuccessful transmission attempt the CAF increases *CW* and selects a new random delay for another backoff before attempting a retransmission. *CW* is incremented as one less than powers of two until CW reaches CW_{max}. CW remains at this value until it is reset to CW_{min}. When a transmission is successful the CAF has become the TXOP holder. This means that the TXOP holder can undergo multiple frame exchanges, separated by SIFS, so long as the total duration of the TXOP does not exceed $TXOP_{\text{limit}}$. Following a TXOP where the final transmission was successful *CW* is reset. It can also be reset once a retry limit is reached. Also, following a TXOP where the final transmission was successful the backoff procedure shall be invoked once more to reduce the probability of a packet collision.

The request to send/clear to send (RTS/CTS) mechanism is an optional feature that can be used in a frame exchange sequence. Here, the transmitting CAF first sends an RTS frame which describes the time required for the rest of the frame exchange. If this is successfully received the receiving station returns a CTS frame which also contains timing information on the frame exchange. Any neighbouring stations that hear either the RTS or CTS frame now know about the rest of the frame exchange sequence so refrain from transmitting during this time. This mechanism is particularly useful when the frame being sent is large and/or when there are hidden station issues (i.e. not all stations in the network can hear one another and so carrier-sense is not reliable).

The above description uses immediate positive acknowledgements although it is possible to send packets that do not use acknowledgements. Also block acknowledgements can be used to improve efficiency.

The ECMA-392 standard defines a superframe structure. Within this superframe is a beacon period at the start and a contention signalling window at the end. There are also two additional optional windows; a reservation-based signalling window, and a quiet period. The rest of the superframe is the data transfer period (DTP). Within the DTP both channel reservation access (CRA) and prioritized contention access (PCA) are permitted. More information on the various components of the superframe can be found in [3]. In this paper we just focus on the behaviour of PCA.

PCA behaves in a very similar way to 802.11 EDCA. Packets are mapped into ACs and have the same parameter set list, although parameter values may not be the same. TXOPs are contended for in the same manner. However, the backoff rules have some slight differences from those of 802.11 and so are explained here.

The rules for adjusting CW and invoking the backoff procedure are described in section 7.5.1.7 of the ECMA-392 standard. There is a general rule for updating CW which states that following a successful frame transmission a station will reset CW to CW_{min}. This agrees with the rules of 802.11. However there are some specific rules, A to F, which determine how CW is adjusted when invoking the backoff procedure. In the event that both the general rule and the specific rules would both modify CW, then the specific rule is applied instead of the general rule (Note: This section of ECMA-392 can be a little ambiguous but this interpretation has been confirmed from discussions with the editor of the standard). This is only the case for rules B and

C which apply following a successful transmission when that transmission is the final frame exchange in the TXOP. Rule B applies when the current CAF has no further frames in its buffer to send; in this case backoff is invoked with CW reset to $CW_{\min}$. Rule C applies when the CAF still has frames in its buffer but the TXOP is not long enough for further frame transactions; in this case backoff is invoked with CW remaining at its current value (i.e. CW is not reset). These rules, B and C, show that ECMA-392 stations are using the current buffer status to determine whether or not to reset CW. During high loads, CW is reset less, resulting in fewer transmission attempts. In other words, during a high load these rules aim to reduce network congestion (collisions). The aim of this paper is to demonstrate how these rules can cause an ECMA-392 PCA-type system to exhibit significantly different behaviour to an 802.11 EDCA-type system.

There are ways that an ECMA-392 PCA system can behave more like an 802.11 EDCA system. First of all, as explained above, rules B and C only apply for transmissions that are the CAF's final frame transmission in a TXOP. This means that if a TXOP contains more than one frame exchange CW will already have been reset before the final frame exchange in the TXOP takes place. ECMA-392 currently states fixed channel access parameters and the TXOP values are relatively short compared to 802.11 (NB: in 802.11 the recommended value for best-effort and background ACs is actually zero but this corresponds to a single frame exchange. Also, in 802.11 the TXOP values for any AC can be updated by parameter set updates). For data transmissions, at most PHY transmission rates, this will mean each TXOP is only large enough for a single frame exchange. These relatively short TXOP values allow ECMA-392 to share bandwidth more fairly on a short timescale. However, if an ECMA-392 system wished to behave in a more aggressive manner, it could use fragmentation to allow for multiple frames per TXOP at the expense of the extra overheads associated with fragmentation. Conversely, if an ECMA-392 system wished to behave in a more conservative manner, it could try ensure that each TXOP only contains one frame transmission; this could involve frame aggregation for example. Another way to make an ECMA-392 PCA system behave more like an 802.11 EDCA system is to use the RTS/CTS mechanism. This way, even when a TXOP only has one data frame to send, more than one frame will actually be transmitted. As a result CW will be reset following the successful transmission of the RTS frame.

For this paper we compare the more conservative ECMA-392 PCA-type performance (i.e. only resetting CW following a successful TXOP when that CAF's buffer is empty) with the more aggressive 802.11 EDCA-type performance (i.e. resetting CW after every successful TXOP). For this to be the case, and for the comparison of mechanisms

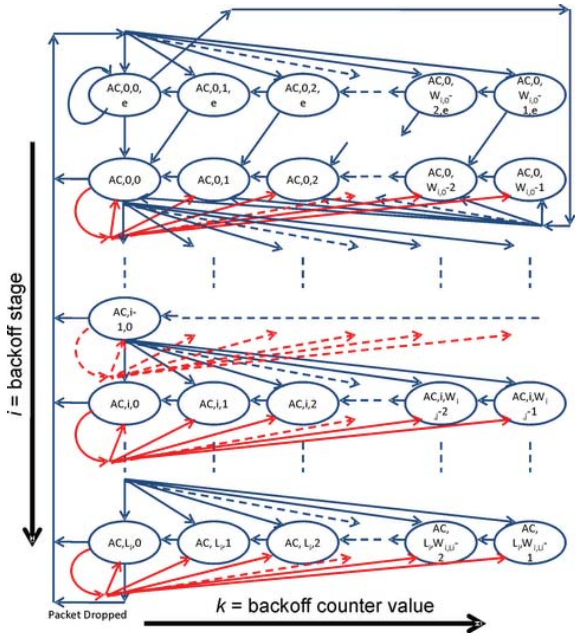

Fig. 1. Markov chain to compare the backoff behaviour of the 802.11 EDCA (blue transitions only) and ECMA-392 PCA (red and blue transitions) protocols.

to be fair, we make several assumptions:

- Each TXOP only contains one data packet. The effect is that an ECMA-392 PCA-type system will only reset CW following a successful TXOP when that AC has an empty buffer; otherwise CW will remain at its current value.
- For the ECMA-392 PCA-type system we assume PCA is used in a continuous DTP. This way overheads associated with the ECMA-392 superframe structure, where PCA would not be contending for the channel, are ignored. Likewise, we assume that an 802.11 EDCA-type system is always able to contend for the channel.
- The same physical layer is used under both MAC mechanisms so that we are comparing the MAC performance fairly.

Markov chains are one of the best ways to analyze the performance of EDCA. Figure 1 shows a Markov chain used in [12] for EDCA. This is one of the more advanced models as it considers all of the EDCA parameters, multiple ACs and non-saturated loads. The state transmission probabilities are not shown as this diagram is only used to provide a visual comparison of how the EDCA and PCA backoff mechanisms differ. The states are labelled (AC, i, k) where AC is the CAF being modelled, i is the backoff level and k is the current backoff value. The states labelled (AC, i, k, e) represent states where backoff is performed while a CAF queue is empty. States with values of $k = 0$ are the transmitting states. The blue lines reflect the transitions available in EDCA, while PCA also includes the added red lines. Following a successful TXOP EDCA will select a new backoff value in the top level in the Markov chain ($i = 0$) whereas PCA will only do this if its transmission queue is currently empty (or the TXOP contains more than one frame exchange). Otherwise PCA will remain at the same level in the Markov chain to start the backoff procedure for the next transmission.

3. EFFECTIVE MARKOV CHAIN SOLVING

Everything we compute is derived from a *transition matrix* P, so that P_{ij} is the probability of moving from state i to state j. (In reality states have labels which are integer tuples $(i_0, i_1, \dots)$, but we ignore this complication here.) We need the *equilibrium vector* z, which is a solution of $z^{\mathrm{T}}(I-P) = 0$. Properties of P which must be considered are: the transition matrix P is large, but *sparse*; the transition matrix P is *asymmetric*; and the system of linear equations to be solved is singular and need some additional normalization condition, such as is provided by normalizing z, so that $||z|| = 1$. These properties create difficulties. There can be thousands of states, and then the full P matrix cannot be stored, and in all cases it cannot be manipulated in dense fashion. We found by experience that the best results were obtained by using the Super LU package [13]. We implemented a mapping of integer tuples to integer indices (and its inverse) using C++ hash mappings. The result is a convenient library for solving large Markov chains, with the user input in a natural form and internal re-indexing hidden from the user. The singularity problem is handled by replacing one row of $I-P$ with the equation $||z|| = 1$.

Some of the simpler cases of Markov chain models of wireless backoff have exact analytic solutions. We claim that this is of little help in practice; it is hard to check whether an analytic solution is possible, and if it is, it is easy to make mistakes deriving it. We believe that a single numerical technique, applicable to all cases, such as ours, is better in general.

A particular example of interest is the Bianchi model [14]. This has parameters: W is the minimum contention window plus one; m is the value such that $2^m W$ is the maximum contention window plus one; and p is the packet collision probability, computed from the number of users as shown below. Such a model has $(2^{m+1}-1)W$ states. The states of the system form $m+1$ downward-going "escalators" E_0, E_1, …, E_m of heights W_0, W_1, …, W_m where $W_i = 2^i W$. The states are labelled by (i, k) where $i \in \{0, 1, \dots, m\}$ labels the backoff stage, and $k \in \{0, 1, \dots, W_i-1\}$ is the backoff time counter (height on that escalator). The transmitting states are $(i, 0)$ for $i \in \{0, 1, \dots, m\}$ so the probability of a transmission, τ, is the sum of the probabilities of being in these transmitting states. The dynamics for a saturated 802.11 CAF may be summarized by these rules: From (i, k) with $k \geqslant 1$, move with probability one to state $(i, k-1)$, one step down E_i. From $(i, 0)$ (the bottom of E_i) jump with probability $1-p$ to a random point on escalator E_0. From $(i, 0)$ jump with probability p to a random point on escalator $E_{\min(i+1,m)}$.

In formulae,

$$
\begin{aligned}
p(i,k;i,k-1) &= 1 \quad \forall i \text{ and } 1 \leqslant k \leqslant W_i-1,\\
p(i,0;0,k) &= \frac{1-p}{W_0} \quad \forall i \text{ and } 0 \leqslant k \leqslant W_0-1,\\
p(i,0;i+1,k) &= \frac{p}{W_{i+1}} \text{ for } 0 \leqslant i \leqslant m-1 \text{ and}\\
&\quad\ 0 \leqslant k \leqslant W_{i+1}-1,\\
p(m,0;m,k) &= \frac{p}{W_m} \text{ for } 0 \leqslant k \leqslant W_m-1,
\end{aligned}
$$

where we use $p(i, k; j, l)$ to denote the 1-step transition probability from (i, k) to (j, l).

These rules are adjusted to the following in order to apply to a saturated CAF with ECMA-392 PCA backoff,

$$
\begin{aligned}
p(i,k;i,k-1) &= 1 \quad \forall i \text{ and } 1 \leqslant k \leqslant W_i-1,\\
p(i,0;i,k) &= \frac{1-p}{W_i} \quad \forall i \text{ and } 0 \leqslant k \leqslant W_i-1,\\
p(i,0;i+1,k) &= \frac{p}{W_{i+1}} \text{ for } 0 \leqslant i \leqslant m-1 \text{ and}\\
&\quad\ 0 \leqslant k \leqslant W_{i+1}-1,\\
p(m,0;m,k) &= \frac{p}{W_m} \text{ for } 0 \leqslant k \leqslant W_m-1,
\end{aligned}
$$

This results in a saturated ECMA-392 Markov chain never jumping back down to escalator E_0 and becoming stuck in escalator E_m. This explains the conservative behaviour of the backoff mechanism during high loads.

The solution is also required of a nonlinear equation. The packet collision probability p is related to the number of stations n, the probability P_{tr} of a transmission in a particular timeslot, the probability P_{s} of a transmission being successful, and throughput S by the following equations [14]:

$$
\begin{aligned}
p &= 1-(1-\tau)^{n-1}\\
P_{\mathrm{tr}} &= 1-(1-\tau)^{n}\\
P_{\mathrm{s}} &= \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^{n}}\\
S &= \frac{P_{\mathrm{s}} P_{\mathrm{tr}} E[P]}{(1-P_{\mathrm{tr}})\sigma + P_{\mathrm{tr}} P_{\mathrm{s}} T_{\mathrm{s}} + P_{\mathrm{tr}}(1-P_{\mathrm{s}}) T_{\mathrm{c}}}
\end{aligned}
$$

where $E[P]$ is the average packet payload, σ the timeslot duration, T_{s} and T_{c} the duration of a successful transmission and a collision respectively. Solving the top equation requires an iterative method. An initial estimate of p is used; using this to solve the Markov chain, τ can be calculated. p must then be modified and the Markov chain re-solved until a value of τ is produced that allows for the above equation to be satisfied. For the adjustment of p at each iteration we used the multiroot solver from the GSL library [15].

TABLE 1
TEST PARAMETERS

Access Type	Data Rate (Mbps)	$E[P]$ (μs)	σ (μs)	T_s (μs)	T_c (μs)
Basic	31.65	379	9	490	490
RTS/CTS	31.65	379	9	577	106

4. AGGREGATE INTERFERENCE

During a collision more than one station will attempt to transmit at the same time. These simultaneous transmissions can cause aggregate interference. In this paper we wish to examine the aggregate interference issue by examining how many transmissions are likely to be involved in each collision. We use Pr$[NTX = x]$ to represent the probability that when there is a transmission attempt there are x stations simultaneously attempting transmission. We can generalize the equation for P_s as the probability that when a transmission occurs only one station attempts transmission (i.e. Pr$[NTX = 1]$). So Pr$[NTX = x]$ can be calculated as

$$\Pr[NTX = x] = \frac{\binom{n}{x}\tau^x(1-\tau)^{n-x}}{1-(1-\tau)^n}.$$

5. TEST RESULTS

In this section results are shown to compare the behaviours of 802.11 EDCA and ECMA-392 PCA. Ways to maintain high throughputs using parameter adjustment are investigated while also evaluating the aggregate interference performance.

The above Markov chain analysis is used to provide the analytical results. Further validation is provided by a modified version of the *wlan_mac_hcf* process model from the Opnet Modeler Wireless Suite 16.0 [16]. The physical layer chosen is that of ECMA-392 for an 8 MHz channel. This offers a maximum transmission rate of 31.65Mbps. For each test all stations are saturated with packets that have 1500 byte MSDUs. As mentioned earlier, we assume that each TXOP only contains one data packet and both systems are able to contend for the channel all of the time (i.e. no overheads currently considered such as quiet periods for sensing.). We also assume that channel access parameters are adjustable, which is not currently the case for ECMA-392. So when comparing the behaviours of 802.11 EDCA and ECMA-392 PCA we refer to the behaviour as 802.11 EDCA-type and ECMA-392 PCA-type behaviours respectively. The parameters used for the Markov analysis are shown in Table 1.

For this first set of results we compare 802.11 EDCA-type and ECMA-392 PCA-type behaviours using the same parameter set values. These are $CW_{\min}$ =15 and $CW_{\max}$ =1023, which equate to W=16 and m=6 for the Markov chains used; *AIFSN*=2; *TXOP*=0 (i.e., one frame exchange per contention) and a timeslot duration, σ=9μs. The system performance is evaluated using basic access and also with the RTS/CTS mechanism. It is important to note that when RTS/CTS is used an ECMA-392 PCA system, according to the rules in the standard, would reset CW during a successful frame exchange (as the RTS frame would be seen as a successful frame transmission that is not the final frame transmission in the TXOP). For these tests this would result in the ECMA-392 PCA-type system and the 802.11 EDCA-type system behaving the same as each other when the RTS/CTS mechanism is used. For this first set of results we show the ECMA-392 PCA-type performance with RTS/CTS if CW is only ever reset when the AC has an empty buffer. The reason for this is that we wish to compare conservative and aggressive backoff mechanisms in general rather than simply limiting our choice to existing 802.11 and ECMA-392 specifications. This is also a reason for using the terminology ‘ECMA-392 PCA-type’ and ‘802.11 EDCA-type’.

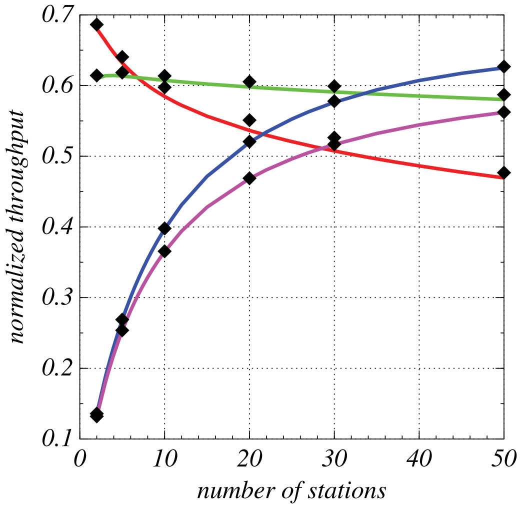

Fig. 2. System capacity results. 802.11 EDCA-type system (red: basic, green: RTS) & ECMA-392 PCA-type system (blue: basic, magenta: RTS). Black diamond=simulation.

Figure 2 shows the performance of the systems under test for networks of varying size. The first thing to note is that, for a network with few stations, an 802.11 EDCA-type system provides a high throughput while the throughput of an ECMA-392 PCA-type system is very low. As the number of stations increases the performance of an ECMA-392 PCA-type system improves while the 802.11 EDCA-type system performance gradually degrades. The best performing mechanism is the 802.11 EDCA-type system with the RTS/CTS mechanism. For the full range of network size tested this mechanism achieves around 60% MAC layer efficiency. For a very small network the 802.11 EDCA-type system performs better without the RTS/CTS mechanism due to the increased overheads in a successful RTS/CTS frame exchange sequence. However as the contention rises for larger networks this overhead is compensated for by the much reduced time spent on collisions (It is worth noting at this point that while the RTS/CTS mechanism reduces time spent on collisions in a congested network it does not reduce the probability of collisions and therefore the aggregate interference issue is not necessarily resolved).

When the network has 50 stations, an ECMA-392 PCA-type system without RTS/CTS shows the best overall performance. Even at this point the overheads in successful RTS/CTS frame exchanges are not compensated for by the reduced overheads in collisions. This tells us that even for a large network an ECMA-392 PCA-type system is successful at avoiding collisions. This conservative approach suggests that it may be more cooperative with other secondary systems than the more aggressive 802.11 EDCA-type system.

Using these channel access parameters, the 802.11 EDCA-type system is the most suitable protocol to use when the number of active stations is low and each station has high capacity demands. Video distribution around the home is a prime example of this type of scenario. Another suitable scenario is indoor-to-outdoor coverage of the street allowing for Internet access to outdoor terminals. When there are a large number of terminals that each require only a low amount of throughput such as machine-to-machine systems, the ECMA-392 PCA-type system is most preferable; it can offer throughput that can compete with the 802.11 EDCA-type system while at the same time being more cooperative with other secondary systems.

The channel access parameters above compare system behaviour using $CW_{\min}$ and $CW_{\max}$ values that are quite common. In fact these are the recommended values for best effort traffic in 802.11 EDCA (The recommended value for $CW_{\min}$ is physical layer dependent but is typically 15 for high rate physical layers) and the fixed values for best effort traffic in ECMA-392 PCA. However, system performance can be greatly improved for each protocol by adjusting the parameter settings to match the current network scenario. Figure 3 shows how we can modify the 802.11 EDCA-type system performance simply by selecting different values for $CW_{\min}$ while fixing $CW_{\max}$ =1023. Here, only $CW_{\min}$ values of one less than powers of two are used. However, we can see that as the network size varies, different values for $CW_{\min}$ allow for the best throughput performance. If the correct value of $CW_{\min}$ is selected then a MAC efficiency of around 65% can be maintained. One of the important points here is that only one parameter is being adjusted and it only takes 6 possible values. With a reasonable estimate of the network size a system can achieve high performance using

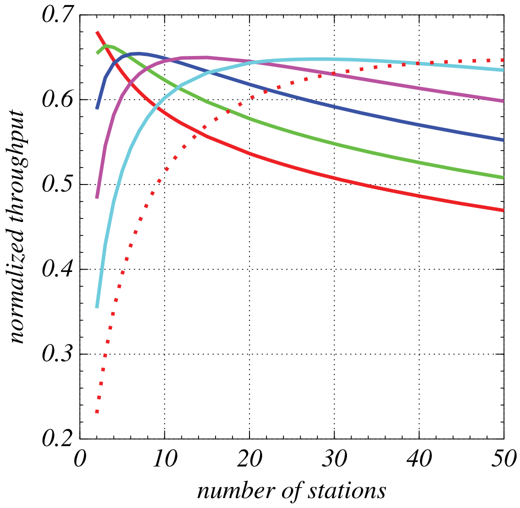

Fig. 3. Adjusting 802.11 EDCA-type system $CW_{\min}$ to maintain high throughput. ($CW_{\min}$ is red: 15; green: 31; blue: 63; magenta: 127; cyan: 255; dotted red: 511).

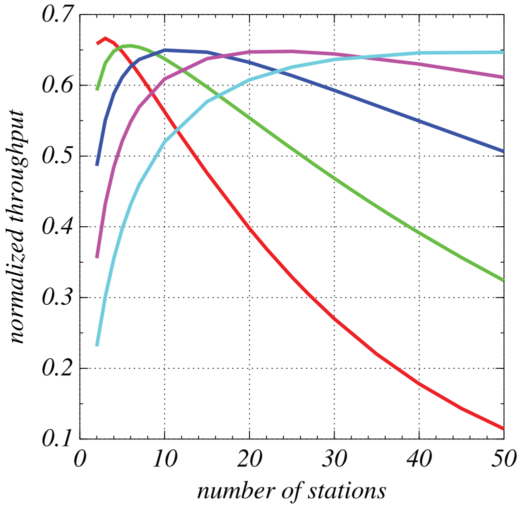

Fig. 4. Adjusting ECMA-392 $CW_{\max}$ to maintain high throughput. ($CW_{\max}$ is red: 31; green: 63; blue: 127; magenta: 255; cyan: 511).

this limited parameter set.

Figure 4 shows how we can modify the ECMA-392 PCA-type performance simply by selecting different values for $CW_{\max}$. Here $CW_{\min}$ =7 (i.e. W=8) and $CW_{\max}$ values are always one less than powers of two. As the network size varies different values for $CW_{\max}$ allow for the best throughput performance. Again, as seen with the previous set of results, if the correct parameter value is selected then a MAC efficiency of around 65% can be maintained. Here only one variable is adjusted and only takes 5 values to cover

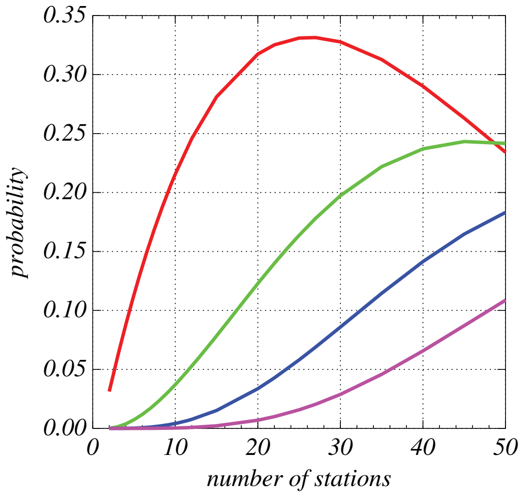

Fig. 5. Collision behaviour of ECMA-392 for $CW_{\min}$ =7 and $CW_{\max}$ =31. (red: $\Pr[NTX = 2]$; green: $\Pr[NTX = 3]$; blue: $\Pr[NTX{=}4]$; magenta: $\Pr[NTX{=}5]$).

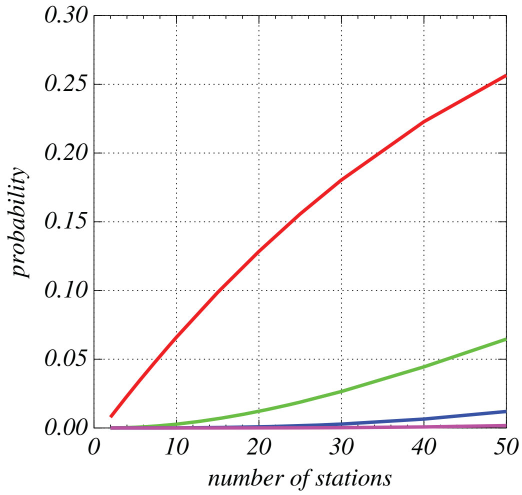

Fig. 6. Collision behaviour of ECMA-392 for $CW_{\min}$ =7 and $CW_{\max}$ =127. (red: $\Pr[NTX = 2]$; green: $\Pr[NTX = 3]$; blue: $\Pr[NTX{=}4]$; magenta: $\Pr[NTX{=}5]$).

various network sizes up to 50 stations.

Limiting aggregate interference is another reason why adjusting parameters might be preferable. When a contention-based protocol is being too aggressive there is a strong possibility of collisions. As this collision probability increases, so does the probability of more stations being involved in each collision. A high collision probability should be avoided for several reasons: (1) the system will suffer a performance degradation (e.g., drop in throughput) as a result of too many failed transmission attempts; and (2) multiple secondary systems may be using the channel. If one system transmits too often it is may not be sharing the channel very well as other secondary systems cannot gain fair access to it. Also the probability of collisions/interference among secondary systems will increase. Furthermore (3), when multiple secondary transmissions cause a collision the aggregate interference should not be able to interfere with any primary systems. For this final reason we look at the collision probability of secondary systems as the parameter settings are adjusted.

Figure 5 shows the collision performance for an ECMA-392 PCA-type system when $CW_{\min}$ =7 and $CW_{\max}$ =31 (i.e. W=8 and $m = 2$). It can be seen that when the network is small, so is the collision probability. As the network grows so does the probability of collisions. The most common form of collision is one involving just two transmissions until the network size approaches 50 stations. However, the probability of collisions with more than two transmissions becomes more of a problem as the network size increases. When the network size is around 12 stations, then about 5% of all transmission attempts involve collisions with three simultaneous transmissions. This 5% mark is reached for 4 simultaneous transmissions when the network size is about 23 stations and for 5 simultaneous transmissions when the network size is about 36 stations. When the system size is 50 stations the aggregate interference becomes a serious concern where the probability of a collision is very high and the number of transmissions involved in any collision is now likely to be more than 2.

As seen from the Figure 4, the same parameters that give these collision behaviour results only have a high throughput for a small network size. Using the example in Figure 4, these parameters would only be recommended operating parameters until the system size reaches about 5 stations. When we re-examine the results in Figure 5 for up to a network size of 5 we see that the collision behaviour of the system is quite good. As the network size reaches 5 stations, the probability of a collision with just two transmissions starts to exceed 10% while the probability of collisions with more than two stations is almost negligible. This demonstrates that the benefit of parameter adjustments can both maintain a high throughput whilst also reducing aggregate interference in a system.

To further demonstrate this point, Figure 6 shows the collision performance of the ECMA-392 PCA-type system for the operating parameters which, according to the results shown in Figure 4, would be recommended to maintain a high thoughput for a system size roughly between 9 and 17 stations (i.e. $CW_{\min}$ =7, $CW_{\max}$ =127 which means W=8, m=4). If we compare Figure 6 to Figure 5 we see that these new parameters are less aggressive and have much lower collision probabilities for higher network sizes. As these parameters approach the largest network size that they are recommended for in order to maintain a high throughput we see again that the probability of a collision with just two transmissions starts to exceed 10% while the probability of collisions with more than two stations is very low.

6. CONCLUSIONS

In this paper the protocol behaviour of the 802.11 and ECMA-392 contention based mechanisms have been described. A comparison of the performance of these types of contention based mechanisms is provided and analyzed. Using the same parameter set 802.11 type systems are more aggresive than ECMA-392 type systems and achieve higher throughputs for small networks, whereas the more conservative ECMA-392 type systems offer better coexistence with other secondary systems using the same channel and better throughput performance for networks with many terminals. Based on these different characteristics, recommendations have been made concerning which TVWS deployment scenarios each mechanism may be better suited to.

We have also investigated the option to adjust parameter values in these mechanisms. By simply adjusting one parameter over a limited range of values a high thoughput can be maintained over a wide range of network sizes. A further benefit of this parameter adjustment has been demonstrated regarding aggregate interference. When using parameters which maintain a high throughput the collision probability of a system is kept low; when there is a collision it is unlikely to involve more than two simultaneous transmissions, which limits the issues of aggregate interference where the secondary system(s) could interfere with the channel's primary user(s).

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