Idle sense with transmission priority in fibre-wireless networks

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Abstract: The convergence of fibre and wireless technologies realised the fibre-wireless (FiWi) networks. Despite huge capacity offered by fibre, the user experiences a network bottleneck caused by the wireless side. This study investigates wireless local area network (WLAN), the wireless side of the FiWi networks with a gigabits passive optical network (GPON) as the backhaul. The work aims to improve WLAN performance by utilising information gained from GPON. The proposed technique enables all contending stations in multiple access points (APs) WLAN to achieve a desired downlink-to-uplink transmission ratio, k while maintaining maximum throughput. Optimum contention window (CW) sizes for the APs and associate wireless users (WUs) are derived by incorporating the principles of idle sense (IS) and asymmetric AP. However, fairness problem between WUs occurred when they contend the channel with different CW sizes. Hence, this study simplifies the IS scheme to increase fairness between WUs. Furthermore, AP self-adapting and WU adjusting algorithms are proposed to assist the network to achieve the desired k, while maintaining the throughput fairness amongst basis service sets. The robustness of the proposed scheme is demonstrated under various conditions: achieved target k with nearly perfect fairness and gained near-to-maximum throughput within 96% of the theoretical optimum.

Nomenclature

\( p_{\text{ap}} \) probability of an AP transmitting
\( p_{\text{wu}} \) probability of a WU transmitting
\( m \) total number of APs (or BSSs)
\( n \) total number of WUs
\( \text{CW}_{\text{ap}} \) current contention window size for an AP
\( \text{CW}_{\text{wu}} \) current contention window size for a WU
\( p_{s,\text{ap}} \) probability that a transmission is a successful AP transmission
\( p_{s,\text{wu}} \) probability that a transmission is a successful WU transmission

1 Introduction

Fibre-wireless (FiWi) networks have evolved as a promising broadband access network as it offers a huge capacity of bandwidth from the fibre and freedom of mobility from the wireless side [1–6]. The survey conducted in [7] found that the European broadband subscriber valuation of fibre to the home (FTTH) connection has increased quickly over time and became significantly higher than the valuation of digital subscriber line at the end of the survey in December 2014. Furthermore, the number of FTTH subscribers in Europe increased by 20.4% since September 2016 with more than 51.6 million FTTH subscribers in September 2017 [8]. This FTTH termination is likely to use wireless distribution throughout the home.

A passive optical network (PON) is adopted as the backhaul for FiWi networks due to its energy efficiency and reliable service provision. The PON in this network acts as a small cell backhaul, a promising solution to satisfy the ever increasing demand for mobile data traffic [9–12]. Previous work in [9] showed a small cell backhaul deployment using PON can halve the cost in comparison with the typical point to point fibre backhauling approach. On the wireless side, the work in [10, 11] proposed wireless mesh networks to provide network survivability and the work in [12] opted to integrate with the WiFi function in small cell backhaul to avoid the huge data loss and traffic outage when a distribution fibre is broken. Similarly, the work in [13] proposed FiWi networks by integrating gigabits passive optical network (GPON) as a small cell backhaul with a ‘closed’ infrastructure wireless local area network (WLAN) in the wireless side, as shown in Fig. 1.

The optical line terminal (OLT) of GPON at the central office is connected to a passive optical splitter, which divides the optical power into m separate paths to the subscribed optical network terminals (ONTs). Each ONT in FiWi networks is directly connected to the AP of the WLAN. In this situation, the operator has a dedicated spectrum allocation, which is shared by all access points (APs). Such a scenario may result in massive traffic congestion if the APs are closely located (adjacent properties or apartment), which is often the case for GPONs in dense urban and sub-urban areas. The congestion gets worse when each AP has an increasing number of associated wireless users (WUs). Hence, this study focuses on the techniques to improve the quality of service (QoS) of the densely deployed WLAN pertaining to the fairness among the transmitting terminals by exploiting the information gained from the GPON side.

In this study, WLAN, using the idle sense (IS)-based medium access control (MAC) method, is chosen as the front end for FiWi integration due to its simplicity, low cost of implementation and its ability to operate in either dedicated or unlicensed spectrum.

In practice, the majority of WLAN deployments operate in an infrastructure mode that comprises an AP serving its associate WUs forming a basic service set (BSS). The same deployment is applied to the front end of the proposed FiWi networks as shown in Fig. 1. In return, the AP in each BSS is the gateway for all the WUs, which requires more transmission opportunities than each WU. However, in the standard IEEE 802.11 distributed coordination function (DCF) access method, every station including the AP is given an equal chance of transmission, which leads to unfairness between uplink (UL) and downlink (DL) transmissions, thus, degrading the QoS in WLAN.

Extensive works have been carried out to mitigate the UL and DL unfairness [14–25]. In common, the schemes propose priority access for the AP. The authors in [18–20, 24] change the CW of the contending stations in accordance with the target DL/UL ratio.
Furthermore, the methods proposed in [22, 23] reduce inter frame spacings (PIFS and SIFS instead of DIFS) of the AP while authors in [24, 25] adjust the transmission opportunity limits of the AP. On the contrary, Umehara et al. [17] proposed a DCF with successful transmission priority only for the UL transmission with the assumption that the AP does not have any data flow to WUs. The scheme provides the success of WUs' priority by using a variety of IFS including SIFS and PIFS. Recently, Katayama et al. [15] proposed the same approach to adjust the back-off time at the AP in order to allocate more DL bandwidth in high-density WLAN.

Alternatively, Ando et al. [16] used a unique synchronised phase (SP) with phase shifting to set the back-off time rather than using a random integer in CSMA/CA. A new amplitude parameter is introduced in the SP technique to allow adjusting the transmission opportunity limits of the AP. The authors in [21] introduced a unique synchronised scheme (SPS) to reduce the collision by allowing the AP to get higher priority for UL transmission. This is an open access article published by the IET under the Creative Commons Attribution License 

2 GPON frame structure

This section describes how the estimation for the number of active ONTs and the size of the downstream channel access algorithms. Furthermore, this study focuses on the fairness problem of multiple APs sharing the same spectrum in the FiWi networks (Fig. 1). We extend the throughput analysis in the AAP scheme [21] to the multiple AP scenario and derived the optimum CW size of the APs.

On the other hand, the IS technique used in the AAP scheme allows every WU to dynamically control its CW size by monitoring the mean number of idle slots between transmission attempts. It is a simple method using a local estimate without involving an intermediate state of estimating the number of WUs, which is difficult to obtain accurately and may cause instability to the system [27]. IS is claimed in [28] as one of the arguably best time fairness-based channel access algorithms. However, it is noteworthy that the previous authors involved in the IS scheme assumed all stations have similar CW sizes [21, 26, 29, 30]. This assumption is not always valid in a real deployment of WLAN because of local interference factors. Therefore, we initiate WU with different CW sizes to test the robustness of the scheme. We show that when the number of APs increases the fairness between WUs deteriorates, caused by the adjustment algorithm in IS. To overcome the problem, we propose an alternative way of achieving the desired UL/DL ratio, fairness, and maximum throughput.

All the techniques proposed in this work do not require information about any unknown variable except for the number of APs, $m$. However, the value of unknown $m$ can be estimated by exploiting information from the GPON. Thus, the following section describes the GPON frame structure. The remaining sections of the paper are organised as follows: Section 3 extends the principles of AAP and IS methods in multiple APs scenario and derives the optimum AP and WU contention window (CW) sizes. Section 4 describes the simulation set up in this work. Section 5 evaluates the performance of IS with transmission priority technique in multiple BSSs environment. Section 6 presents synchronous updates to reduce the fairness problem in the proposed scheme. Sections 7 and 8 propose an AP self-adapting (APSA) and a WU adjustment (WUA) algorithms, respectively, to further improve the fairness of the scheme. Finally, Section 9 concludes the paper.
The spectrum is considered ‘closed’, i.e. a single 20 MHz channel populated urban areas is considered. All BSSs are within close proximity, i.e. all wireless stations, APs and WUs, share one single channel and can hear each other, albeit being potential interferers. The spectrum is considered ‘closed’, i.e. a single 20 MHz channel entirely dedicated to this network. This assumption is inline with the principles of AAP [21] and IS [26, 29]. The aim is to give the APs an infinite number of trials until the packet is successfully transmitted.

### 3 Transmission priority in multiple APs scenario

This section analytically derives optimum CW sizes for an AP and a WU in the WLAN network. Our proposed network scenario resembles the wireless side of the FiWi network architecture. It comprises $m$-integrated ONTs–APs and $n$-associated WUs, where each AP serves its own BSS of $n/m$-associated WUs. The worst case scenario in terms of frequency availability in densely populated urban areas is considered. All BSSs are within close proximity, i.e. all wireless stations, APs and WUs, share one single channel and can hear each other, albeit being potential interferers. The spectrum is considered ‘closed’, i.e. a single 20 MHz channel entirely dedicated to this network. This assumption is inline with the concept of the small cell backhaul in FiWi networks as proposed in [9, 10, 12]. It is also assumed that all stations always have packets to transmit (i.e. greedy stations) and are given an infinite number of trials until the packet is successfully transmitted.

The following analysis is carried out by combining the principles of AAP [21] and IS [26, 29]. The aim is to give the APs and WUs the priorities to have the required bandwidth, which is defined as the number of successful transmissions of APs with respect to WUs.

Let $\beta$ be a WU in the WLAN network. Our proposed network scenario comprises an integrated ONT-AP and an AP of WLAN are incorporated into a single GPON and an AP of WLAN are incorporated into a single FiWi hybrid system (also known as radio and fibre system) [1–3, 5]. The integrated ONT–AP device acts as a gateway translating MAC frames from the optical network to the wireless network and vice versa. Two distinct separate MAC protocols are used to access GPON and WLAN, respectively. Thus, the wireless MAC frames only traverse the WLAN and do not have to travel along the optical fibre to be processed at the central office, avoiding the negative impact of the fibre propagation delay on the side performance by using the information gained from the GPON to estimate $m$. The following section will present how the estimate $m$ is utilised to improve WLAN performance.

### 3.1 Transmission probability

The transmission probability $p_i$ of a station $i$ is given by:

$$p_i = 1 - (1 - p_{ap})^n \cdot (1 - p_{wu})^m,$$

where $p_{ap}$ and $p_{wu}$ are the probability of an AP and a WU transmitting, respectively. See Nomenclature section for a list of notations. The probabilities $p_{ap}$ and $p_{wu}$ are independent of each other and are given by the following based on Bianchi’s model in [33]:

$$p_{ap} = \frac{2}{(CW_{ap} + 1)},$$

and

$$p_{wu} = \frac{2}{(CW_{wu} + 1)}.$$  

Furthermore, the probability that a transmission is a successful AP transmission $P_{opt}^s$ is given by the probability that only one AP transmits on the channel provided that there is a transmission

$\lim_{n \to \infty} (1 - p_{ap})^n \cdot \lim_{n \to \infty} \left(1 - (\frac{\beta}{n})^m\right) 
\approx \beta.$  

Using (10) and (11) in (9) leads to
\[ \alpha = \beta - m \ln(km) + m \ln(\beta + km). \]  

We can numerically solve (12) to get the value of \( \beta \) as the value of \( k, m, \) and \( \alpha \) are known. The variable \( m \) is estimated from the GPON frame format information described in Section 2 and the constant \( \alpha \) can be obtained by solving \( 1 - \alpha = (1 - (T_{\text{slot}}/T_c))e^{-\alpha} \), a minimised cost function derived in [26]. Then, from (8), we have

\[ P_{\text{ap}} = \frac{\beta}{\beta + km} \]  

and from (2), we have

\[ \text{CW}_{\text{ap}} = \frac{2(\beta + km)}{\beta} - 1. \]  

Furthermore, as stated before \( n_{\text{wu}} = \beta \), then

\[ P_{\text{wu}} = \frac{\beta}{n}. \]  

and from (3), we have

\[ \text{CW}_{\text{wu}} = \frac{2n}{\beta} - 1. \]  

All variables in CW size formulations are assumed known and the required MAC and physical layer (PHY) parameters are listed in Table 1.

The derived formulations are validated in terms of saturation throughput. Bianchi’s model in [33] is used to analyse the normalised saturation throughput, \( S \). Refer to the Appendix in Section 12 for a full derivation of (17)

\[ S = \frac{P_{\text{ap}}P_{\text{wu}}T_{\text{payload}}}{(1 - P_{\text{ap}})T_i + P_{\text{ap}}P_{\text{wu}}T_s + (1 - P_{\text{wu}})P_{\text{ap}}T_c}. \]  

where \( T_{\text{payload}} \) is the average time taken to transmit the payload, \( T_i \) is the idle slot time defined in the IEEE 802.11 standard [34], \( T_s \) is the average time the channel is sensed busy by each station due to a successful transmission, and \( T_c \) is the average time the channel is sensed busy by each station due to a collision. The values of \( T_i \) and \( T_c \) depend on PHY and MAC layers’ parameters (defined in IEEE 802.11 standard as listed in Table 1), which can be expressed as

\[ T_s = T_{\text{payload}} + \text{SIFS} + T_{\text{ACK}} + \text{DIFS} \]  

and

\[ T_c = T_{\text{payload}} + \text{DIFS}. \]  

In addition, the UL throughput \( S_{\text{wu}} \) and DL throughput \( S_{\text{ap}} \) are expressed as follows:

\[ S_{\text{wu}} = \frac{P_{\text{ap}}^\text{wu}P_{\text{wu}}T_{\text{payload}}}{(1 - P_{\text{wu}})T_i + P_{\text{ap}}P_{\text{wu}}T_s + (1 - P_{\text{ap}})P_{\text{wu}}T_c} \]  

and

\[ S_{\text{ap}} = \frac{P_{\text{ap}}^\text{ap}P_{\text{ap}}T_{\text{payload}}}{(1 - P_{\text{ap}})T_i + P_{\text{ap}}P_{\text{ap}}T_s + (1 - P_{\text{ap}})P_{\text{ap}}T_c}. \]  

The throughput is evaluated analytically using (17), (20), and (21), when every station employs a fixed value of \( \text{CW}_{\text{ap}} \) and \( \text{CW}_{\text{wu}} \) derived in (14) and (16), respectively. All variables in CW size formulations are assumed known in order to obtain the ideal throughputs, known as target throughput. Table 2 presents the optimal CW size for APs and WUs as we increase the number of BSSs from 1 to 30 with the transmission priority factor, \( k \), set equal to 1.

| m  | n  | \( CW_{\text{ap}} \) | \( CW_{\text{wu}} \) |
|----|----|---------------------|---------------------|
| 1  | 4  | 16                  | 57                  |
| 2  | 8  | 30                  | 117                 |
| 3  | 12 | 45                  | 176                 |
| 4  | 16 | 60                  | 236                 |
| 5  | 20 | 75                  | 296                 |
| 10 | 40 | 150                 | 595                 |
| 15 | 60 | 225                 | 894                 |
| 20 | 80 | 299                 | 1193                |
| 25 | 100| 374                 | 1492                |
| 30 | 120| 449                 | 1791                |

Fig. 4 Normalised saturation throughput versus \( m \), number of BSSs (simulation and theory)

The plotted curves (using MATLAB software) in Fig. 4 show the target (theoretical) throughputs (\( S \), \( S_{\text{wu}} \) and \( S_{\text{ap}} \)) when the number of BSSs increases. The curves \( S_{\text{wu}} \) and \( S_{\text{ap}} \) are overlaid as expected for \( k = 1 \).

### 4 Simulation setup

In this work, the performance of all proposed schemes is evaluated by means of simulation carried out using OPNET Modeler 16.1 software. OPNET is a commercial packet level simulator. It accurately models the behaviour for any kind of network. The WLAN is modelled based on simulation parameters from the IEEE802.11a standard, as listed in Table 1. Every BSS comprises one integrated ONT-AP serving four WUs. Every station is assumed continuously transmitting with a constant packet size of 8184 bits.
where \( I \) is the number of idle slots observed between two transmission attempts and \( M \) is the maximum number of transmission attempts (note: differs from \( m = \) the estimated number of integrated ONT-APs). The refined IS algorithm in [29] sets the value of \( M \) depending on the accuracy of the estimate \( \hat{I} \). If the difference between estimate \( \hat{I} \) and target value \( I_t \) is within 0.75, \( M \) becomes one-quarter of the CW size or else \( M \) is reduced to five in order to speed up convergence when the estimate is clearly off target. Fig. 4 indicates that the obtained total throughput \( S \) is within 97% of the target throughput when the WUs use IS as their adaptation mechanism. Furthermore, it is also observed that when the number of BSSs increases, the DL throughput \( S_{\text{ap}} \) is \( \sim 8\% \) lower than its target throughput, whereas the UL throughput \( S_{\text{wu}} \) is about \( 3\% \) higher than its target throughput. Therefore, the resultant \( S_{\text{wu}}/S_{\text{ap}} \) ratio \( k_{\text{mix}} \) is nearly \( 8\% \) lower than target \( k \). Overall, the obtained results are comparable to the respective target values with a minor difference, which is not significant, most probably resulted from the effect of the AIMD algorithm as discussed in [35].

However, it is surprising to note that the fairness in channel utilisation, \( F \), deteriorates as the number of BSSs grows dropping below 0.5 when \( m \geq 12 \) (Fig. 6). Jain's fairness index, \( F \), is given by the spread in \( CW_{\text{wu}} \) over all WUs at the end of the simulation

\[
F = \frac{\left( \sum_{k=1}^{M} 0.5 \cdot \frac{2}{CW_{\text{wu}} + k} \right)^2}{n \cdot \left( \sum_{k=1}^{M} 0.5 \cdot \frac{2}{CW_{\text{wu}} + k} \right)^2} \tag{24}
\]

The range of \( F \) lies within 0–1, where a value closer to 1 implies better fairness [36]. The figure shows that good fairness is only possible when the network size is small (\( m \leq 5 \)).

According to the principle of IS, all contending stations, using the IS scheme, are trying to reach the target value \( I_t \) and set their transmission probabilities to target \( P_{\text{opt}} \). The relationship is given by

\[
I_t = \frac{1 - P_{\text{opt}}}{P_{\text{opt}}} \tag{25}
\]

Hence, from (1), the CW sizes of all WUs will ideally converge to the target value

\[
CW_{\text{wu}}^{\text{opt}} = \frac{2}{1 - \left(1 - P_{\text{opt}}\right) \cdot \left(1 - \frac{1}{M^{\text{opt}}}ight)} - 1 \tag{26}
\]

irrespective of their initial \( CW_{\text{wu}} \) states. However, this is not always the case as shown next. When the network is large (large \( m \), large \( n \)), every WU adapts to a different value of \( CW \) as illustrated in Fig. 7. The figure shows the cdf of \( CW_{\text{wu}} \) for a network with \( m = 30 \) APs having fixed \( CW_{\text{ap}}^{\text{opt}} \), and \( n = 120 \) WUs contending the channel using the IS scheme. At the beginning of the simulation (\( t = 0 \) s) every WU contends the channel with a CW size randomly chosen within the range (16, 2\( CW_{\text{ap}}^{\text{opt}} \)). After 50 s, the CW sizes of all WUs do not show any sign that they will converge to the common value but diverge away from the initial states. Finally, as the time approaches 100 s, two classes of CW sizes are created where the first class dominates most of the channel bandwidths while the second class starves. The huge gap between the two classes of CW sizes anticipates the instability of the scheme and further deteriorating the fairness between all WUs.

Despite the fact that one class of WUs are starving and growing poor throughput, it does not deteriorate \( S_{\text{wu}} \) as it is supported by another class of WUs, which hog the channel, contributing more throughput for the UL, \( S_{\text{ap}} \). Therefore, the resultant \( k_{\text{mix}} \) is still close to the target value and the channel utilisation remains unaffected by the instability of the IS scheme. It is worth noting that the resultant \( S_{\text{ap}} \) also remains unaffected because all the APs use a fixed CW size.
As expected, the accuracy of the estimate $\hat{I}$ increases with $M$. The mean of the estimate $I (= E(\hat{I}))$ for $M = 1000$ varies within 3% of the target value, $I$, compared to 47% for $M = 5$. It is also observed that lower $I$ estimates cause the CW$_{wu}$ sizes to converge to lower than optimum values giving the WUs more chances to transmit. As a result, CW$_{wu}$ increases and deteriorates the fairness between DL and UL transmissions. Note that CW$_{ap}$ remains fixed. For example, with $M = 5$ resulted in CW$_{wu}$ = 826 some 54% lower than target. Thus, allowing the WUs to gain higher throughput (S$_{wu}$ = 0.293, 28% higher than target) and worsen the fairness between DL and UL as indicated by the 109% increase in $k_{\text{mea}}$ to 2.09. Moreover, the reduction in CW$_{wu}$ causes increased collisions which degrade the overall throughput by 5%; somewhat less than anticipated considering the almost halving of the CW$_{wu}$.

Conversely, setting $M = 1000$ improves all metrics. CW$_{wu}$ converges to within 93% of the optimum target value, and the fairness between UL and DL is significantly improved ($k_{\text{mea}} = 1.08$) to within 92% of its target value. Furthermore, the variance in CW$_{wu}$ reduces as $M$ increases, implying that the throughput fairness between WUs is also improved.

In spite of higher $M$ giving better performance, it requires a longer time to converge. The comparison summary in Table 3 reveals that the convergence time is directly proportional to $M$. For example, the convergence time for $M = 1000$ is about 200 times longer than $M = 5$. Clearly, the benefits of better performance are offset by the downside of longer convergence time. Therefore, in this study, we choose $M = 20$ as a good compromise value. Although fairness, $k$, is much improved (cf. $M = 5$), it is still 65% away from the desired value. In the following section, we propose an alternative algorithm to improve fairness without jeopardising the convergence time.

7 AP self-adapting algorithm

This section proposes the AP self-adapting (APSA) algorithm to assist the network to achieve the desired $k$. This approach requires every AP in the network to monitor the measured S$_{wu}$/S$_{ap}$ ($= k_{\text{mea}}$) in its respective BSS by counting the number of successfully transmitted packets, $P_d$ (forming the DL throughput S$_{wu}$) and the received packets, $P_a$ (forming the UL throughput S$_{ap}$). Each AP periodically adjusts its CW$_{wu}$ after every $P_a$ transmissions so that the observed $k_{\text{mea}}$ will reach the desired $k$. The AP alters its CW size by $\delta$, where

$$\delta = \frac{P_a - k \times P_d}{\max (k \times P_d, P_a)} \times \text{CW}_{ap}. \tag{27}$$

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$$\delta = \frac{P_a - k \times P_d}{\max (k \times P_d, P_a)} \times \text{CW}_{ap}. \tag{27}$$

6 Synchronous updates

In a study of an ad hoc WLAN (i.e. with $m = 0$), Hassan et al. [35] concluded that the fairness problem in the IS scheme arose due to the combined effects of bias in the AIMD algorithm, non-synchronous updating of the CW, and the varying length of $M$ among stations. As an alternative solution, one of these three factors is removed, the varying length of $M$ is fixed to allow synchronous updates across all stations. Therefore, each station has an equal chance of updating its CW sizes and will eventually converge to the common value to achieve perfect fairness as demonstrated by the vertical line in Fig. 7 for $M = 20$.

Table 3 summarises the comparison between different values of $M$ ($M = 5, 20$, and 1000) pertaining to their performance metrics.
Fig. 9 Cdf of CW$_{ap}$ with 120 WUs (from 30 BSSs) contending stations for different $P_{set} = 30, 100$ and $300$ ($k = 1$ and $\varphi = 1$)

Fig. 10 Convergence time for one AP in the network with 30 BSSs to reach the desired $k = 1$ for different $P_{set} = 30, 100$, and $300$ with $\varphi = 1$

Fig. 11 Fairness between APs for networks with $k = 0.5, 1$, and $2$

Fig. 12 Normalised saturation throughputs (total, DL, and UL) for 30 BSSs network scenario as the network's target $k$ varies from 0.25 to 4

Table 4 Equilibrium throughput for five BSSs having different target $k$

| $k$ | $n^1$ | $S_{ap}$ | $S_{wu}$ | $S$ | $S_{ap}$ | $S_{wu}$ | $S$ |
|-----|-------|---------|---------|-----|---------|---------|-----|
| 1   | 4     | 0.039   | 0.039   | 0.078| 0.044   | 0.045   | 0.089|
| 1   | 4     | 0.039   | 0.038   | 0.077| 0.044   | 0.045   | 0.089|
| 0.5 | 4     | 0.078   | 0.039   | 0.117| 0.059   | 0.029   | 0.088|
| 0.5 | 4     | 0.078   | 0.039   | 0.117| 0.059   | 0.029   | 0.088|
| 2   | 4     | 0.020   | 0.039   | 0.059| 0.030   | 0.059   | 0.089|

12 depicts the throughput performance of 30 BSSs when target $k$ varies from 0.25 to 4. It is evident that throughput is within 96% of the theoretical optimum, indicating $k_{mea}$ remains close to the $k$. Thus, the APSA algorithm can handle a wide range of $m$ and $k$.

Furthermore, we evaluate the performance of the IS+APSA scheme when five BSSs operate in the same spectrum but with different priority factors $k$, as specified in Table 4. By comparing the throughput columns, $S_{ap}$ and $S_{wu}$ (without WUA), every BSS achieves target $k$, corroborating the effectiveness of the APSA and IS algorithms. Every AP plays its role to maintain the $k_{mea}$ within the set target $k$ in its BSS while all the WUs equally share the remaining bandwidth using the IS scheme.

Therefore, each BSS gains equal UL throughput $S_{wu}$ (column 2) irrespective of target $k$. However, the DL throughput $S_{ap}$ is inversely proportional to target $k$ (i.e. the higher $k$, the lower the DL throughput $S_{ap}$), validating the impact of the APSA algorithm. For instance, for the case $k = 0.5$, the AP keeps on reducing its CW size in order to ensure the DL throughput ($S_{ap}$) is twice the UL throughput ($S_{wu}$), while for $k = 2$, it keeps on increasing its CW size to ensure $S_{ap}$ is half of the $S_{wu}$. This unbalance behaviour affects the throughput fairness amongst BSSs as demonstrated in Table 4 (column 3). The two BSSs with $k = 0.5$ dominate 52% of the total throughput leaving two BSSs with $k = 1$ and one BSS with $k = 2$ to obtain 35 and 13% of the total throughput, respectively. The following section suggests a technique to equalise the fairness amongst BSSs.

8 WUA algorithm

The WUA algorithm introduces a mechanism to ensure the chance of a WU to transmit is dependent on target $k$ set in its respective BSS so that the total throughput per BSS across the network is fairly equalised. Consider a network, which comprises $m$ BSSs. Each BSS ($j = 1, 2, 3...m$) has one AP with $n^j$ number of WUs and it independently sets target $k$. Every $j$th BSS has a probability of $p_{ij}$ of a successful transmission in either DL or UL directions, given from (6) as
\[ p'_i = \left(1 + \frac{1}{k_i}\right)p_w \]  

(28)

where \( p_w \) is the probability that any one of the \( n' \) WUs successfully transmits a packet without incurring any collision

\[ p'_w = n'p_w(1 - p_c) \]  

(29)

Note that \( p_c \) is the probability of a collision, which is assumed constant across the network, because all the contending stations use the same transmission rate and packet size. Moreover, \( p'_w \) is the probability of WUs from BSS\(^1\) transmitting after contending with the channel with the CW size of \( CW_{wu} \)

\[ p'_i = p'_w - \frac{2}{n'(1 + \frac{1}{k_i})} \]  

(31)

such that when \( k = 1 \) and \( n' = 1 \) there is no scaling. To achieve this, \( p'_w \) in (30) is altered at the WU to

\[ p'_w = \frac{2p_w}{n'(1 + \frac{1}{k_i})} \]  

(32)

by scaling the CW. Substituting (3) into (32) and assuming \( CW \gg 1 \)

\[ CW_{wu} = \frac{n'(1 + \frac{1}{k_i})}{2} \]  

(33)

In summary, the above analysis suggests that every WU scales its current \( CW_{wu} \) after being updated by IS with a factor of \((n'(1 + \frac{1}{k_i})/2)\) before contending the channel. The WU only needs to know local information pertaining to its BSS's \( n' \) and \( k_i \). The former is available by monitoring the traffic from the AP and identifying its address fields and the latter must be periodically broadcast from the AP\(^2\).

The simulation scenario described in Table 4 is repeated using the WUA algorithm. The UL throughput \( S_{wu} \) in each BSS varies with the set priority target \( k' \), and \( n' \) such that every BSS is forced to have an equal throughput, \( S \) (column 6) irrespective of \( k' \). Note the measured \( k_{max} \) remains close to the target value, \( k' \).

The previous simulations assumed the number of users per BSS is fixed at \( n' = 4 \). Table 5 shows results for variable \( n' \) per BSS. There are still \( m = 5 \) APs and \( n = 20 \) WUs, but the WUs are no longer evenly spread between the BSSs. In all cases, the APSA algorithm maintains the measured \( k_{max} = S_{wu}/S_{ap} \) close to the target, while the IS algorithm remains constant throughput per WU. The total throughput \( S \) per BSS (column 3) is now dependent on both \( n' \) and \( k \). The fairness is restored between BSSs when the WUA algorithm is included. Also, note the total throughput, \( S \), is independent of \( n' \), which means the more WUs, the less throughput each gets.

Finally, the robustness of the network is evaluated when all \( m = 30 \) APs and \( n = 120 \) WUs in the combined IS, APSA, and WUA schemes. The plot in Fig. 13 demonstrates the convergence behaviour of \( k_{max} \) when target \( k \) changes across the network. It is evident that the proposed scheme quickly responds to the changes in \( k \): 5 s are required for the network to change from \( k = 1 \) to \( k = 2 \) and a similar time to change from \( k = 2 \) to \( k = 0.5 \). However, a somewhat longer 12 s is required for 15 BSSSs to reach \( k_{max} = 2 \) (from \( k_{max} = 0.5 \)) while the other 15 BSSSs remain at their \( k = 0.5 \) setting. At this state, despite \( k \) difference, both classes of BSSSs have almost equal throughputs, with the difference being < 1.5% as indicated by \( S_{BSSS} \) values in Fig. 13.

### 9 Conclusions

This study proposed a series of schemes to improve the performance of the WLAN in multiple BSSSs scenario, which resembles the wireless side of the FiWi networks. The performance of the wireless component is optimised by taking advantage of the common fibre connection going to all the integrated ONT–APs and the broadcast nature of the GPON downstream transmission from which \( m \) number of active ONT–AP can be estimated. The estimate \( m \) is then used in our proposed scheme to compute the optimum \( CW_{ap} \) size (12)–(14). Alternatively, the \( CW_{ap} \) values can be pre-calculated and stored in a look-up table. The study analytically extends the AAP scheme into the multiple BSSSs scenario. Priority is given to the APs by using constant CW sizes (analytically derived) while the WUs equally share the remaining bandwidth using the IS adaptation method. The study revealed two classes of users, those that dominate transmissions and those that starve. Instability arises when bias from the AIMD convergence process interacts with the adaptive idle slot-sensing mechanism. Therefore, the IS scheme is simplified by forcing all WUSs to a fixed IS sensing period. As a result, the fairness between WUs is improved but UL/ DL fairness, \( k_{max} \) remains a problem. Thus, every AP periodically adjusts its \( CW_{ap} \) to reach the desired UL/DL throughput target, \( k \). However, the IS+APSA algorithm generates unfairness between BSSSs with different \( k \) targets. The WUA algorithm recuperates the fairness between BSSSs by scaling the current \( CW_{wu} \) based on the required \( k' \) and the number of BSS users. The network achieves the desired fairness between UL and

| Table 5 | Equilibrium throughput for five BSSSs having different target \( k \) and \( n' \) |
|---------|-----------------|-----------------|-----------------|-----------------|
| \( j \)  | \( k \)  | \( n' \) | \( S_{ap} \) | \( S_{wu} \) | \( S \) | \( S_{ap} \) | \( S_{wu} \) | \( S \) |
| 1       | 1     | 2     | 0.020  | 0.020  | 0.040  | 0.046  | 0.045  | 0.091 |
| 2       | 1     | 6     | 0.059  | 0.057  | 0.116  | 0.045  | 0.043  | 0.088 |
| 3       | 0.5   | 2     | 0.039  | 0.019  | 0.058  | 0.060  | 0.029  | 0.089 |
| 4       | 0.5   | 6     | 0.119  | 0.057  | 0.176  | 0.060  | 0.029  | 0.089 |
| 5       | 2     | 4     | 0.020  | 0.038  | 0.058  | 0.030  | 0.059  | 0.089 |

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DL as well as between BSSs while maintaining the difference of throughputs within 4% of theoretical optimum. The network responds to changes in \( k \) within a maximum of 12 s. In conclusion, the combined IS+APSA+WUA scheme is well fitted for the wireless side (WLAN networks with multiple BSSs sharing the same frequency channel) of the FiWi network. Each station in the BSS is given a fair transmission opportunity to fully utilise the huge bandwidth capacity provided by the GPON (backhaul). Further work is required to evaluate the accuracy of the estimate \( m \) obtained from the GPON and consequently analyse the backhaul effect of FiWi networks on our proposed algorithms.

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## 12 Appendix

### 12.1 Full derivation of saturation throughput \( S \)

Considering the fact that the contention of a radio channel can evolve between three states: idle ‘\( i \)’, collision ‘\( c \)’, and successful transmission ‘\( s \)’, which gives

\[
p_i + p_c + p_s = 1.
\]

By definition, normalised saturation throughput \( S \) is expressed as the fraction of the time the channel is used to successfully transmit payload bits

\[
S = \frac{p_i T_{\text{payload}}}{p_i T_i + p_c T_c + p_s T_s}.
\]  

Note that collision and successful transmission states give the impression that the channel is busy indicating that there is at least one transmission on the channel. Hence, the transmission probability \( p_t \) is

\[
p_t = p_c + p_s.
\]

which further yields

\[
p_t + p_s = 1.
\]

where
\[ P_c = \frac{P_c}{P_u} \quad \text{(38)} \]
\[ P_s = \frac{P_s}{P_u} \quad \text{(39)} \]

Corroborating (34) and (36) gives

\[ P_c = 1 - P_u \quad \text{(40)} \]

Finally, using (35), (38)–(40), the normalised saturation throughput \( S \) is derived

\[ S = \frac{P_c P_u T_{\text{payload}}}{(1 - P_u) T_s + P_u P_s T_s + (1 - P_s) P_u T_c} \]