Compound TCP Performance for *Industry 4.0* WiFi: A Cognitive Federated Learning Approach

Shiva Raj Pokhrel, *Member, IEEE*, and Surjit Singh

***Abstract*—Understanding the performance of compound transmission control protocol (C-TCP) in wireless settings is complicated because of C-TCP's hybrid congestion control, and the complex interdependencies between losses due to wireless channel errors, medium access control (MAC)-layer collisions, and access point (AP) buffer overflows. In this article, we develop a comprehensive model to study the performance of long-lived C-TCP flows over Industry 4.0 WiFi infrastructure, taking all losses into account. Our mathematical model includes WiFi system parameters, such as the retransmissions limit and the AP buffer size, in order to see how they affect transport-layer throughput and fairness. More importantly, we extend the analytical model to multiple APs, and compare the performance of a dual AP scenario with a conventional single AP scenario. Our results show that using cognitive radio and federated learning techniques in the industrial multiple APs scenario can substantially improve the performance.**

***Index Terms*—Cognitive radio (CR), compound transmission control protocol (TCP), correlated losses, federated learning (FL), IEEE 802.11 WiFi, multiple access points (APs).**

I. Introduction

WIFI networks provide ubiquitous and inexpensive Internet access using IEEE 802.11 standard-compliant technology [1], [2]. This makes them attractive for delivering last-mile Internet services to end users in areas where existing alternatives, such as WIMAX, 5G/LTE, cable, and optical fiber, are too expensive or infeasible. In infrastructure-based industrial IEEE 802.11 WiFi [3], wireless stations (STAs) or devices associate with an access point (AP). They use random channel access techniques, and connect to the Internet via their associated AP, typically using the transmission control protocol (TCP). However, TCP performance over conventional WiFi networks is limited with a single shared AP [3], [4], and may not scale well in wide-area Industry 4.0 networks where wireless channels are reused by multiple APs.

Multi-AP scenarios [i.e., an enhanced form of multiuser multi-in multi-out (MIMO)] are a promising approach to boost the capacity of wireless LANs (WLANs) by transmitting downlink data streams to multiple devices concurrently. This approach increases the achievable data rate by a factor equal to the number of antennas or APs. Whenever downlink multiuser MIMO is enabled in a WiFi network, multiple APs can provide wireless access to many users. However, the same WiFi channels may be used by different APs in overlapping areas, resulting in interference that can make TCP transfers over the conventional WiFi MAC inefficient [5], [6]. Specifically, the packet losses caused by channel errors, collisions, and AP buffer overflows can severely degrade the performance and compromise privacy of long-lived flows for applications like video streaming and large file transfers. Therefore, we exploit federated learning (FL) [7]–[9] and cognitive radio (CR) techniques [10], [11] with multiple APs to improve TCP performance over industry WiFi networks. In a different context, Sangaiah *et al.* [12], [13] proposed energy aware modeling and machine learning paradigm for such Industry 4.0 systems.

The congestion control mechanisms in de facto TCP versions, such as TCP NewReno, are less effective in high-speed and long-distance networks [14]. For this reason, Tan *et al.* [15] proposed compound TCP (C-TCP) as an enhanced algorithm that combines both loss-based and delay-based congestion control to improve performance in networks with a large bandwidth-delay product (BDP) [14]. C-TCP is the default in earlier versions of the Windows operating system, but has recently been replaced by TCP CUBIC. Therefore, understanding and improving the performance of C-TCP over WiFi is essential for the Industry 4.0 wireless systems.

In the context of WiFi networks, Hasanni *et al.* [2] regulated the sending rate at the transport layer to achieve high throughput while avoiding excessive queuing delay [2, Fig. 16]. Other techniques, such as FL and CR, have been investigated from different perspectives [16], such as dynamic channel selection [17], throughput analysis [7], [18], interference sensing [19], and cognitive AP selection [11], [20]. The emerging Internet of Things requires future wireless devices and APs to be equipped with cognitive intelligence in order to monitor the surrounding RF environment, make informed decisions, and be more energy-efficient (see [21] for a survey and [22] and [23] for AP coordination approaches). In this regard, this article aims to

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Shiva Raj Pokhrel is with the School of Information Technology, Deakin University, Geelong, VIC 3220, Australia (e-mail: shiva.pokhrel@deakin.edu.au).

Surjit Singh is with the Thapar Institute of Engineering and Technology, Patiala 147004, India (e-mail: surjitmehla@gmail.com).

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develop techniques for the analysis and design of CR approaches in future multi-AP WiFi networks. Earlier works [1], [4], [24] consider both MAC-layer losses and AP buffer overflows, but only for a single AP. Furthermore, one of these works [4] used a fixed transmission loss probability for all users, which is not realistic in practice, and the other [24] modeled only the downloading scenario. Capturing the coupling between uploads and downloads with C-TCP traffic is challenging in WiFi, and is an important feature in our model (Section III-C).

Given this context, a complete understanding of the correlation among losses due to heterogeneous channel errors for different users, MAC-layer collisions, and AP buffer overflows, and their impacts on C-TCP performance for upload and download flows over 802.11 WLAN, is lacking in the literature. Therefore, we develop a comprehensive analysis of C-TCP over WiFi with multiple APs, accounting for all three types of losses. In fact, prior TCP-over-wireless models used a single loss parameter, which cannot accurately predict the behavior of C-TCP [15] over WiFi networks. To address this issue, we model C-TCP behavior using a two-layer loss process that separates MAC-layer loss from AP buffer loss, and improve the model proposed in [15] and [24]. This segregation of the losses quantifies the impact of correlated losses on the C-TCP dynamics. To the best of our knowledge, our work is the first to systematically evaluate the performance of C-TCP with multiple APs while considering the uploading and downloading dynamics of WiFi with correlated losses. We also enhance the WiFi performance using FL and with CR approaches (Section IV-A).

In our analysis, we provide a rigorous derivation of the cross-layer loss parameters (as perceived by C-TCP) in terms of the MAC layer and the AP buffer, and extend our analysis to multiple APs.

In summary, the main contributions of this article are as follows.

- C_1) We develop a novel analytical model to study the impacts of collisions, wireless losses, and AP buffer losses on C-TCP over WiFi with bidirectional flows.

We extend our model to multiple APs to improve the performance of C-TCP over Industry 4.0 WiFi. The dual AP approach proposed in this article improves performance by increasing the number of saturated nodes. The performance improvement with respect to the single AP case is illustrated with numerical, simulation, and experimental results.

- C_2) We implement FL and CR approaches to the problem, and evaluate the performance of C-TCP over WiFi with FL and CR techniques in the dual AP scenario.

A. Organization

The rest of this article is organized as follows. Section II discusses FL and C-TCP in detail. Section III introduces our analytical model, which uses a fixed-point approach. Subsequently, Section IV extends the model to the case of multiple APs. Section V presents simulation, numerical, and experimental results to validate the proposed model. Finally, Section VI concludes this article.

II. Background and Concepts

A. Federated Learning

Consider a set of M APs in our system and let each AP collects a set of QoS data samples and computes their local learning update. The local learning update of the mth AP is then sent to the federal coordinator. Our federated training is a regression problem that focuses on solving the problem in parallel for a global vector v (say). Our objective is to [7]–[9]

$$\text{Minimize } \mathcal{F}(v), \text{ where}$$

$$\mathcal{F}(v) = \frac{\sum^{M} \sum_{d_i \in s_m} (h_i^{\intercal} v - B_i)^2/2}{|S|} \tag{1}$$

for convenience, $d_i = \{h_i, B_i\} \in S$ denote the ith data sample. With FL [8], [9], it is well-known that the default idea to solve (1) is to perform local training at each AP by using the stochastic gradient algorithm, followed by a global training for aggregating local updates via distributed Newton's method. FL mandates data privacy, which is vital for Industry 4.0 communication. In each stage, the local model is recomputed with the number of iterations. Given the step size $\delta > 0$, the local vector denoted by v_n is updated after every iteration. Every AP in this learning sends $(v_n, \nabla \mathcal{F}_j(v))$, the local update, to the federal coordinator, which then computes the global update, i.e., $(v, \nabla \mathcal{F}(v))$.

B. Compound TCP

C-TCP uses a hybrid congestion control strategy with both loss-based and delay-based congestion windows [15]. It utilizes both round trip time (RTT) and packet loss as feedback signals to maintain its flow and congestion control mechanisms. The loss-based congestion window W_{loss} is the same as in the standard TCP Reno algorithm, whereas the delay-based congestion window W_{delay} provides additional feedback about the packet latency in the network. The effective sending window of C-TCP [15] is computed as $W = \min\{W_{\text{loss}} + W_{\text{delay}}, W_{\max}\}$, where $W_{\max}$ is the maximum receiver advertised window for flow control. By recording the minimal (base) RTT observed so far, RTT_b, C-TCP maintains a variable dif that is updated as follows:

$$\text{dif} = \text{RTT}_b \left(\frac{W}{\text{RTT}_b} - \frac{W}{\text{RTT}} \right). \tag{2}$$

In essence, this variable provides information about the difference between the actual and expected sending rates. More specifically, it estimates the number of backlogged packets in the network buffer.

The C-TCP congestion window update algorithm in the congestion avoidance phase is [15]

$$W(t+1) = \begin{cases} (W(t)1 + (\alpha(W(t))^k - 1)^+), & \text{if dif} < \text{th} \\ (W(t+1) - \zeta\text{dif}), & \text{if dif} > \text{th} \\ \frac{W_{\text{loss}}(t)}{2} + W_{\text{delay}}(t)(1-\beta), & \text{if loss} \end{cases} \tag{3}$$

TABLE I
MATHEMATICAL NOTATION USED IN MODEL

	Inputs
$N_{u,i}$	Number of uploading devices in error class i
$N_{d,i}$	Number of downloading devices in error class i
K	Maximum MAC re-transmissions per frame (K=7)
D	Maximum number of MAC losses for which the back-off window is doubled (D=5)
p_w	Probability that a packet transmission fails due to wireless error.
$W_{\max}$	TCP Receiver advertised window
B_{Ap}	Buffer size of the APs (in packets)
F	Fairness Index
	Internal Variables
$\Pi(u,d,i)$	Probability that u active uploading and d active downloading devices are belonging to error class i
P_s^u	Probability that the success belongs to uploading devices given that it is successful
P_s^d	Probability that the success belongs to the AP given that it is successful with AP holding TCP DATA at the head-of line (HOL) position
$p_{\mathrm{u,i}}$	Probability that a TCP DATA packet is discarded by an uploading station of error class i
$p_{\mathrm{d,i}}$	Probability that a TCP DATA packet belonging to downloading connection of error class i is discarded from the AP
p_b	Probability that the AP buffer is full and overflows.
h_i	Ratio of services from the AP that are TCP DATA packets of downloading connections; (equal to the probability that the HOL packet at the AP is a TCP DATA packet) belonging to connections of error class i.
$E[\Gamma]$	Expected number of losses in a renewal cycle
$E[\tau]$	Expected number of attempts in a renewal cycle
$\Theta_{u,i}^{\mathrm{TCP}}$	Expected TCP Throughput of uploading connections (in packets/second) belonging to error class i
$\Theta_{d,i}^{\mathrm{TCP}}$	Expected TCP Throughput of downloading connections (in packets/second) belonging to error class i
$\mathbb{E}(u,d,i)[X]$	Expected duration of a renewal cycle for error class i
$\gamma_{u,i}$	Transmission loss probability for an uploading device of error class i
$\gamma_{d,i}$	Transmission loss probability from the AP to the downloading device of error class i
	Outputs
p_b	Probability of buffer being full at the AP or the probability that a packet arriving to the AP is blocked
$p_{u,i}$	Packet discard probability of an uploading connection belonging to error class i
$p_{d,i}$	Packet discard probability of a downloading connection belonging to error class i
$\Theta_{u,i}^{\mathrm{TCP}}$	Expected TCP throughput of uploading connections (in packets/second) of error class i
$\Theta_{d,i}^{\mathrm{TCP}}$	Expected TCP throughput of downloading connections (in packets/second) of error class i

where loss is indicated by triple duplicate ACKs, $(.)^+$ is defined as $\max(.,0)$, $\zeta > 0$, and th is a minimum threshold number of backlogged packets to detect the onset of congestion. The latter represents a tradeoff between throughput and buffering delay; we use th $= 30$ packets as in [15]. In (3), the parameters α, β, and k affect the scalability, smoothness, and responsiveness of the window function. The default values are $\alpha = 0.125$, $\beta = 0.5$, and $k = 0.75$ [15].

III. ANALYTICAL MODEL

Table I summarizes the notation used in this article.

A. C-TCP Model

In a low-delay network where dif $<$ th, $W(t+1)$ in (3) can be computed as

$$W(t+1) = \begin{cases} W(t)(1-\beta), & \text{if a packet loss} \\ W(t)\left(1+\alpha W^{k-1}(t)\right), & \text{if all packet success} \end{cases}. \quad (4)$$

Using (4), a generalized fluid model for the congestion avoidance phase of C-TCP is

$$\frac{dW(t)}{dt} = \left(\alpha W^{k-1}(t)(1-p(t-\mathrm{RTT})) - \beta W(t)p(t-\mathrm{RTT})\right)\frac{W(t-\mathrm{RTT})}{\mathrm{RTT}} \quad (5)$$

where RTT represents the mean round trip time and $p(.)$ is the packet loss probability. Different forms of $p(.)$ would be appropriate for various buffer policies and channel conditions. The time period between two consecutive packet losses is called a loss-free interval [15].

1) Packet Loss Process: We define the following model for the packet loss process. Let $S_n = l_{n+1} - l_n$ denote the sequence of intervals between loss instants, where, $\{l_n\}_{n=-\infty}^{n=\infty}$ is the sequence of time instants at which packets are lost. Then, the correlation function for the interloss interval process is $C(i) := \mathbb{E}[S_n S_{n+i}]$. We know that the C-TCP throughput at time t is given by

$$\theta(t) = \frac{W(t)}{\mathrm{RTT}}, \text{ therefore, } \frac{d\theta}{dt} = \frac{1}{\mathrm{RTT}}\frac{dW}{dt}. \quad (6)$$

Considering the loss-free interval between loss instants, for which $p(.) = 0$, dW/dt can be computed[1] by using (5)

$$\frac{dW}{dt} = \alpha\frac{W^k}{\mathrm{RTT}}. \quad (7)$$

Combining (6) with (7) yields

$$\frac{d\theta}{dt} = \alpha\frac{W^k}{\mathrm{RTT}^2}. \quad (8)$$

Equation (8) shows that $\theta(t)$ increases linearly with W^k, but with slope α/RTT^2. Let θ_n be the C-TCP throughput just before the nth loss at loss instant l_n. Then

$$\theta_{n+1} = (1-\beta)\theta_n + \alpha\frac{S_n W^k}{\mathrm{RTT}^2}. \quad (9)$$

Observe that (9) is a stochastic linear differential equation, for which a solution is given by

$$\theta_n^* = \frac{\alpha W^k}{\mathrm{RTT}^2}\sum_{i=0}^{\infty}(1-\beta)^i S_{n-1-i}. \quad (10)$$

[1] We assume that the RTT remains constant during a cycle.

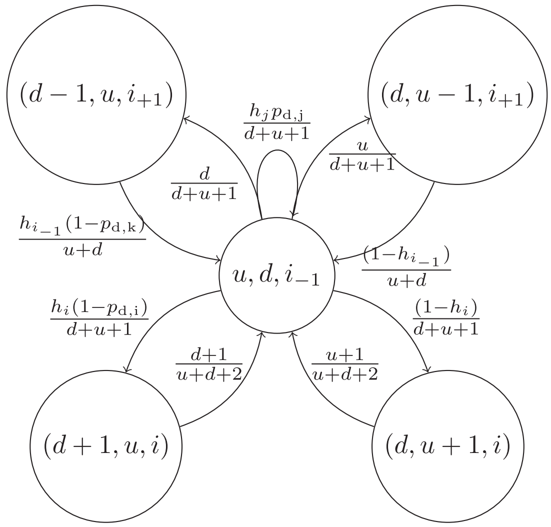

Fig. 1. Partial state transition diagram of $\{(U_k, D_k, I_k)\}$.

B. AP Buffering Analysis

Consider M APs, each of which can store up to B_{Ap} packets. Let d be the round-trip propagation delay of the wired connection between the APs and the server in seconds. Our objective is to obtain the probability p_b of AP buffer overflow. The number of TCP packets in the network at any given point in time obeys the BDP formula in (6).

1) BDP Analysis: The APs serve C-TCP connections from all error classes. Let Θ^{WiFi} be the throughput of the network with multiple APs. Then, we can estimate the maximum number of packets in the network as

$$\begin{aligned} \mathrm{BDP}^{\mathrm{WiFi}}_{\text{in packets}} &\approx \Theta^{\mathrm{WiFi}}\mathrm{RTT} \\ &= \Theta^{\mathrm{WiFi}} d + M B_{\mathrm{Ap}} \\ &= \left(\sum_i \Theta^{\mathrm{TCP}}_{u,i} + \sum_i \Theta^{\mathrm{TCP}}_{d,i}\right) d + M B_{\mathrm{Ap}} \end{aligned} \tag{11}$$

where the upload throughput $\Theta^{\mathrm{TCP}}_{u,i}$ and the download throughput $\Theta^{\mathrm{TCP}}_{d,i}$ are quantities given in packets per second.

2) Buffer Loss Analysis: Given all the parameters in (11), one can compute $\mathrm{BDP}^{\mathrm{WiFi}}_{\text{in packets}}$ easily. Furthermore, we utilize the computed $\mathrm{BDP}^{\mathrm{WiFi}}_{\text{in packets}}$ to obtain the combined loss p using (6). The value of p_b is obtained by separating the wireless packet discard probability $p_{d,i}$ from the overall loss p, using

$$p_b = \frac{p - \sum_i p_{d,i}}{\sum_i (1 - p_{d,i})}. \tag{12}$$

C. TCP-MAC Interaction

We capture the essential features for the cross-layer analysis by using a Markovian process that tracks the evolution of backlogged devices over time (see Fig. 1). The modeling of the evolution of MAC channel activity in the IEEE 802.11 WLAN is similar to that in [4] and [25].

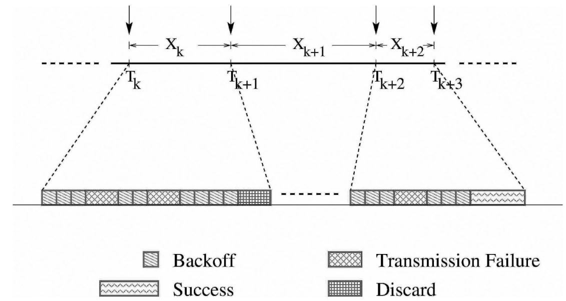

Fig. 2. Renewal channel activity in the IEEE 802.11 WLAN. Marked by arrows are time instants immediately after the service completion. A random variable of duration X_k represents the duration between two consecutive arrows, which is a *renewal cycle*. The (renewal) cycle completes with either a discard or a successful transmission.

1) Evolution of Contending Users: To this end, we make use of the following assumptions as in [4] and [22].

1) The AP buffer is backlogged with packets and always contending for the channel.
   This behavior is observed in *ns-3* simulation and also confirmed by experiments [1].
2) A wireless device has one TCP packet in its buffer.
   These assumptions hold in practice due to the flow control of TCP. The rationale for these assumptions are as argued in [4].
3) The impact from lost TCP ACKs is negligible.

TCP ACKs are cumulative, and the packets containing TCP ACKs are quite short. Thus, the impact of ACK loss under realistic wireless channel errors is negligible [4].

Let h_i denote the probability that the HOL of the AP's queue is a TCP DATA packet belonging to a downloading user of error class i. Let $p_{d,i}$ be the corresponding probability that the service of a TCP DATA packet from the AP belonging to error class i is a MAC discard. We consider a process $\{(U_k, D_k, I_k)$ for $k \geq 0\}$, as illustrated in Fig. 2. embedded at $T_k, k \geq 0$, (the time instants immediately after service in the MAC channel) where D_k and U_k represent the number of contending (backlogged) downloading and uploading devices, respectively, I_k is the error class to which HOL packet at the AP's MAC queue belongs at T_k. Given h_i and $p_{d,i}$, the process $\{(U_k, D_k, I_k), k \geq 0\}$ is a discrete-time Markov chain (DTMC) with state space $\mathcal{S} = \{(u, d, i) : d \geq 0, u \geq 0, 0 < i \geq C\}$.[2] Since $X_{k+1} - X_k$ depends only on (U_k, D_k, I_k), the states $\{((U_k, D_k, I_k), k \geq 0\}$ form a Markov renewal sequence. Notice that $(U_k, D_k, I_k) = (u, d, i)$ implies that $u + d$ backlogged devices and one AP are contending for the channel access when the HOL packet belongs to error class i. The partial state transition diagram of the DTMC $\{(U_k, D_k, I_k), k \geq 0\}$ is depicted in Fig. 1. The transition probabilities, for example, are as follows:

$$\Pr((d, u-1, i)/(u, d, i)) = \ u/(d+u+1)$$
$$\Pr((d-1, u, i)/(u, d, i)) = \ d/(d+u+1)$$

[2]Note that we allow the number of backlogged uploading and downloading devices to exceed $N_{u,i}$ and $N_{d,i}$. This does not affect the accuracy of the analysis when $N_{u,i}$ and $N_{d,i}$ are sufficiently large since the probabilities of the number of backlogged devices exceeding $N_{u,i}$ and $N_{d,i}$ are very low for this DTMC.

$$\begin{aligned}\Pr((d+1,u,i)/(u,d,i)) &= h_i(1-p_{d,i})/(d+u+1)\\ \Pr((u,d,i)/(u,d,i)) &= h_i p_{d,i}/(d+u+1)\\ \Pr((d,u+1,i)/(u,d,i)) &= (1-h_i)/(d+u+1).\end{aligned}$$

The balance equations of the DTMC $\{(U_k, D_k, I_k)\}$ are solved to obtain the stationary distribution $\Pi(u,d,i)$, $u,d \geq 0$, since it satisfies the reversibility criteria. The closed-form expression, obtained with infinite state space, is

$$\Pi(u,d,i) = \frac{d+u+1}{(2-h_i p_{d,i})e^{1-h_i p_{d,i}}} \times \frac{(h_i(1-p_{d,i}))^d (1-h_i)^u}{d!u!}. \tag{13}$$

The expected number of backlogged users is given by

$$E[D]+E[U] = \frac{(1-h_i p_{d,i})(3-h_i p_{d,i})}{(2-h_i p_{d,i})}.$$

Since $0 \leq h_i, p_{d,i} \leq 1$ are small, the expected number of active devices without wireless channel errors is ≈ 1.5.

2) MAC Layer Loss Analysis: Let $\beta_{k,u}$ represent the total number of MAC transmission attempts by uploading users up to the end of the k-th renewal cycle, and let $\Gamma_{k,u}$ represent the corresponding total number of MAC losses due to collisions or wireless channel errors during this time. The conditional loss probability $\gamma_{u,i}$ for uploading users in error class i can be obtained by using

$$\gamma_{u,i} := \lim_{k\to\infty} \frac{\Gamma_{k,u}}{\beta_{k,u}} \approx \frac{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)\mathbb{E}^u_{(u,d,i)}[\Gamma]}{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)\mathbb{E}^u_{(u,d,i)}[\tau]} \tag{14}$$

where $\mathbb{E}^u_{(u,d,i)}[\tau]$ and $\mathbb{E}^u_{(u,d,i)}[\Gamma]$ denote the mean number of attempts and losses, respectively, per cycle by the uploading users given that there are u uploading users and d downloading users backlogged and contending. Similarly, the expected loss probability as observed by the downloading user, $\gamma_{d,i}$, belonging to error class i is given by

$$\gamma_{d,i} \approx \frac{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)\mathbb{E}^d_{(u,d,i)}[\Gamma]}{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)\mathbb{E}^d_{(u,d,i)}[\tau]} \tag{15}$$

where $\mathbb{E}^d_{(u,d,i)}[\tau]$ and $\mathbb{E}^d_{(u,d,i)}[\Gamma]$ denote the mean number of attempts and losses, respectively, per renewal cycle for the downloading user given that there are u upload users and d download users backlogged while the HOL packet at the AP belongs to the user of error class i.

The corresponding packet discard probabilities for users belonging to error class i are given by

$$p_{u,i} = (\gamma_{u,i})^{K+1} \quad \text{and} \quad p_{d,i} = (\gamma_{d,i})^{K+1} \tag{16}$$

where K denotes the maximum allowed number of (re)transmissions of a packet before a discard. Equations (14)–(16) *jointly build the required submodel to estimate MAC level loss* as observed by the C-TCP uploading and downloading users.

The expectation $\mathbb{E}^u_{(u,d,i)}[\tau]$ in (14) satisfies the following recurrence relation:

$$\begin{aligned}\mathbb{E}^u_{(u,d,i)}[\tau] &= P_i(u,d,i)\mathbb{E}^u_{(u,d,i)}[\tau] + P_{su}(u,d,i)\\ &\quad + P_{cu}(u,d,i)(1+\mathbb{E}^u_{(u,d,i)}[\tau])\\ &\quad + (P_c(u,d,i) - P_{cu}(u,d,i))\mathbb{E}^u_{(u,d,i)}[\tau] \end{aligned}\tag{17}$$

which after rearrangement provides $\mathbb{E}^u_{(u,d,i)}[\tau]$. The computation of the other four expected values ($\mathbb{E}(u,d,i)^u[\Gamma]$, $\mathbb{E}(u,d,i)^d[\tau]$, $\mathbb{E}(u,d,i)^u[\Gamma]$, and $\mathbb{E}(u,d,i)^d[\Gamma]$) follows along the same lines.

3) Computation of TCP Throughput: The successfully transmitted packets from the uploading users contribute to the aggregate uplink throughput. Let $O_{k,u}$ denote the total number of TCP DATA packets successfully transmitted by the uploading connections of users belonging to error class i up to the end of the kth cycle under $X_k = T_{k+1} - T_k$ (see Fig. 2). Then, the aggregate upload throughput, $\Theta^{\text{TCP}}_{u,i}$, of users belonging to error class i is given by

$$\begin{aligned}\Theta^{\text{TCP}}_{u,i} &= \lim_{t\to\infty} \frac{O_{k,u}(t)}{t}\\ &\approx \frac{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)P^u_s(u,d,i)}{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)\mathbb{E}_{(u,d,i)}[X]}\end{aligned} \tag{18}$$

where $\mathbb{E}_{(u,d,i)}[X]$ denotes the expected duration of a cycle. $P^u_s(u,d,i)$ denotes the probability that the cycle terminates due to a successful transmission by an uploading user, given that there are u uploading users and d downloading users backlogged, and the HOL packet at the AP queue is from error class i. Similarly, the download throughput $\Theta^{\text{TCP}}_{d,i}$ of users belonging to error class i is given by

$$\Theta^{\text{TCP}}_{d,i} \approx \frac{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)P^d_s(u,d,i)}{\sum_{u=0}^{N_{u,i}} \sum_{d=0}^{N_{d,i}} \Pi(u,d,i)\mathbb{E}_{(u,d,i)}[X]} \tag{19}$$

where $P^d_s(u,d,i)$ denotes the probability that the cycle terminates due to a success by a downloading user given that there are u uploading users and d downloading users backlogged, and the HOL packet at the AP queue is belonging to error class i.

The expectation $\mathbb{E}_{(u,d,i)}[X]$ is obtained by a renewal argument given as follows:

$$\begin{aligned}\mathbb{E}_{(u,d,i)}[X] &= P_i(u,d,i)(\sigma + \mathbb{E}_{(u,d,i)}[X])\\ &\quad + P_c(u,d,i)(\mathbb{E}_{(u,d,i)}[X] + T_{\text{Col}}(u,d,i))\\ &\quad + (P_s(u,d,i) - P_{sd}(u,d,i))T_{\text{Data}}\\ &\quad + P_{sd}(u,d,i)T_{\text{Ack}}\end{aligned} \tag{20}$$

where σ, T_{col}, T_{Data}, and T_{Ack} denote the slot duration in real (continuous) time for a backoff slot, a loss slot, a slot containing a successful TCP DATA, and a slot containing a successful TCP ACK transmission, respectively. The value $\mathbb{E}_{(u,d,i)}[X]$ can be obtained by rearranging (20).

$$\begin{aligned}P_{s\text{Ap}}(u,d,i) &= \tau_{\text{ap}}(u,d,i)(1-\tau_u(u,d,i))^u\\ &\quad \times (1-\tau_d(u,d,i))^d(1-p_{w,i})\end{aligned}$$

$$\begin{aligned}
P_{sd}(u,d,i) &= d\tau_d(u,d,i)(1-\tau_u(u,d,i))^u \\
&\quad \times (1-\tau_d(u,d,i))^{(d-1)}(1-\tau_{\mathrm{ap}}(u,d,i)) \\
P_{su}(u,d,i) &= u\tau_u(u,d,i)(1-\tau_u(u,d,i))^{(u-1)} \\
&\quad \times (1-\tau_d(u,d,i))^d(1-\tau_{\mathrm{ap}}(u,d,i))(1-p_{w,i}) \\
P_s(u,d,i) &= P_{s\mathrm{Ap}}(u,d,i)+P_{sd}(u,d,i)+P_{su}(u,d,i) \\
P_{c\mathrm{Ap}}(u,d,i) &= \tau_{\mathrm{ap}}(u,d,i)(1-(1-\tau_u(u,d,i))^u \\
&\quad \times (1-\tau_d(u,d,i))^d(1-p_{w,i})) \\
P_{cu}(u,d,i) &= u\tau_u(u,d,i)(1-(1-\tau_u(u,d,i))^{(u-1)} \\
&\quad \times (1-\tau_d(u,d,i))^d(1-\tau_{\mathrm{ap}}(u,d,i))(1-p_{w,i})) \\
P_{cd}(u,d,i) &= u\tau_d(u,d,i)(1-(1-\tau_u(u,d,i))^{(u-1)} \\
&\quad \times (1-\tau_d(u,d,i))^d(1-\tau_{\mathrm{ap}}(u,d,i))) \\
P_c(u,d,i) &= 1-P_i(u,d,i)-P_s(u,d,i). \qquad (21)
\end{aligned}$$

4) MAC Saturation Analysis: As shown in Fig. 2, the activity in the network consists of backoff, collision, and success slots. We denote the stationary transmission attempt probability of a node (per slot) by $\tau_x(u,d,i)$, where the subscript x denotes the type of node (u for uploading, d for downloading, and ap for the AP) and the argument (u,d,i) denotes that there are d downloading and u uploading active nodes and are contending while the HOL packet at the AP queue belongs to a user from error class i. Similarly, the conditional transmission loss probability as observed by a user, given that there are d downloading and u uploading users are backlogged and contending, is denoted by $\gamma_x(u,d,i)$. The quantities $\tau_x(u,d,i)$ and $\gamma_x(u,d,i)$ are coupled through fixed-point equations quite similar to Bianchi [26]. For example, the probability of transmission loss as observed by the AP when its HOL packet is from error class i is given by

$$\begin{aligned}
\gamma_{\mathrm{ap}}(u,d,i) &= 1-(1-\tau_u(u,d,i))^u \\
&\quad \times (1-\tau_d(u,d,i))^d(1-p_{w,i}) \qquad (22)
\end{aligned}$$

where $p_{w,i}$ denotes the transmission loss probability due to wireless channel error. Similarly, given the loss probability as observed by a node, its attempt probability only depends on the backoff parameters such as minimum contention window size, maximum number of retransmissions, etc., and can be written as a known function $G(\cdot)$ (see [26]), i.e., $\tau_x(u,d,i) = G(\gamma_x(u,d,i))$, where the quantities $\tau_x(u,d,i)$ and $\gamma_x(u,d,i)$ can be obtained by solving the fixed-point equation $\tau_x = G(.)$ for each (u,d,i).

Once the attempt probabilities $\tau_x(u,d,i)$ have been obtained for each (u,d,i), the probability that a slot is an idle slot is given by

$$\begin{aligned}
P_i(u,d,i) &= (1-\tau_{\mathrm{ap}}(u,d,i))(1-\tau_u(u,d,i))^u \\
&\quad \times (1-\tau_d(u,d,i))^d. \qquad (23)
\end{aligned}$$

The probability of successful transmission of a packet from the AP ($P_{s\mathrm{Ap}}(u,d,i)$), a downloading node ($P_{sd}(u,d,i)$), an uploading node ($P_{su}(u,d,i)$), and any node ($P_s(u,d,i)$) is given by the set of equations in (21). Similarly, the probability that a slot is a collision slot involving the AP ($P_{c\mathrm{Ap}}(u,d,i)$), a downloading node ($P_{sd}(u,d,i)$), an uploading node ($P_{su}(u,d,i)$) or that it a collision slot ($P_c(u,d,i)$) is given by the corresponding equations enlisted in (21).

In (21), the probabilities $P_s^u(u,d,i)$ and $P_s^d(u,d,i)$ are given by

$$P_s^u(u,d,i) = \frac{P_{su}(u,d,i)}{P_s(u,d,i)} \quad \text{and} \quad P_s^d = \frac{P_{sd}(u,d,i)}{P_s(u,d,i)}. \qquad (24)$$

D. HOL Analysis

Let $\lambda_{\mathrm{ap}}^{\mathrm{Data}}$ and $\lambda_{\mathrm{ap}}^{\mathrm{Ack}}$ denote the arrival rates of TCP DATA packets and TCP ACKs, respectively, at the bottleneck AP buffer. Uploading TCP users suffer only due to channel errors, but downloading TCP users suffer due to both buffer loss and channel errors. In steady state, the number of TCP DATA packets entering the AP buffer determines this outcome. The probability h_i that the HOL packet at the AP buffer is a TCP DATA packet from error class i is given by

$$h_i = \frac{\lambda_{\mathrm{Ap},i}^{\mathrm{Data}}}{\lambda_{\mathrm{ap}}^{\mathrm{Data}}+\lambda_{\mathrm{ap}}^{\mathrm{Ack}}} = \frac{\Theta_{d,i}^{\mathrm{TCP}}\frac{(1-p_b)}{(1-p_{d,i})}}{\sum_i \Theta_{d,i}^{\mathrm{TCP}}\frac{(1-p_b)}{(1-p_{d,i})}+\sum_i \Theta_{u,i}}. \qquad (25)$$

E. Fixed-Point Iteration

Define the vectors $\boldsymbol{x} = (h_i, p_{d,i})$ and $\boldsymbol{\Pi}_i = (\Pi(u,d,i), 0 \le d \le N_{d,i}, 0 \le u \le N_{u,i}), 1 \le i \le C)$. At each iteration n of the fixed-point analysis, we start at a point $\boldsymbol{x}_n$ and apply (3)–(15) to compute a new point $\boldsymbol{x}_{n+1}$. In our work, we have observed that $\boldsymbol{x}_n$ converges to the same solution regardless of the initial values; however, the proof of convergence to a unique solution remains for future work. The value of $\boldsymbol{x}$ obtained can be used to calculate the stationary probabilities and the throughput using (18) and (19).

IV. Analysis for Multiple AP Scenario

A. Dual AP Cognitive Communication

In the dual AP scenario[3] considered in this article, we do not distinguish between primary and secondary APs. We assume that both APs have cognitive capability, so that coordination between the two APs can improve the overall TCP throughput. Besides, we also consider the possibility of employing CR techniques such as dynamic sensing at the terminal side. In the considered dual AP scenario, the following three types of interference sources may exist:

1) adjacent channel interference from transmissions in adjacent or partially overlapped channels;
2) intrasystem cochannel interference caused by other APs/users using the same set of channels;
3) intersystem cochannel interference from other external wireless systems such as 4G/LTE.

In this regard, the main role of CR techniques comes in mitigating the harmful interference and/or in allocating the available

[3] Although the CR approaches described here can be extended for any number of APs, we consider only the dual AP scenario for simplicity.

TABLE II
SIMULATION/EXPERIMENTAL PARAMETERS

RTS/CTS	*disabled*	PHY rate	$54\ Mbps$
Control rate	$2\ Mbps$	PLCP preamble	$144\ \mu s$
Slot Time	$9\ \mu s$	DIFS time	$34\ \mu s$
SIFS time	$16\ \mu s$	EIFS time	$308\ \mu s$
Max. Retry limit	7	TCP version	*Compound*
Delayed Ack	*disabled*	TCP Header	$20\ bytes$
IP Header	$20\ bytes$	TCP ACK size	$40\ bytes$
Data size	$1460\ bytes$	Wired bandwidth	$100\ Mbps$
propagation delay	$100\ ms$		

resources (e.g., transmit power, RF channel) effectively. For our analysis, we consider the collision probability as observed in the dual AP case without any cognitive capabilities as $P_{c2\text{Ap}}$, given by

$$P_{c2\text{Ap}}(u,d,i) = \tau_{\text{ap}}(u,d,i)(1-(1-\tau_u(u,d,i))^u \times (1-\tau_d(u,d,i))^d(1-\tau_{\text{ap}}(u,d,i)) \times (1-p_{w,i})) \tag{26}$$

and the minimum collision probability we can obtain after employing some suitable CR techniques as $P_{c2\text{Ap}}\text{Cog}$, given by

$$P_{c2\text{Ap}}\text{Cog}(u,d,i) = \tau_{\text{ap}}(u,d,i)(1-(1-\tau_u(u,d,i))^u \times (1-\tau_d(u,d,i))^d(1-p_{w,i})). \tag{27}$$

B. With FL

We apply the insights from our TCP-MAC interaction (25), delay (11), and TCP-level loss (16) analysis to formulate the FL problem. In particular, the desired level of reliability and latency can only be implemented by learning from private QoS parameters (reflect newfangled dynamics timely) locally at the APs while monitoring (and mandating) the global system capacity and its stability continually from the (federal) coordinator [7].

1) Local Learning Policy: Local policy at each AP has two phases [7]. PHASE-I: Monitor and control delay D_i (by continuously observing the deviation of queue occupancy) and admitting traffic belonging to each device into the AP buffer only when ($<B_{\text{Ap}}$), and forward current deviation of delay and loss probability to the federal coordinator. PHASE-II: Continuously track the packet arrival rates (by observing the deviation of $h_i(t)$ from the required h_i^*) and admitting traffic belonging to each device into the AP buffer only with desired probability $1-p_i(h_i^*)$.

2) Global Learning Policy: Global policy at the (federal) coordinator aims at maintaining low standing queues at all APs [7]. It computes short-term aggregate of the loss and latency information provided by the APs and compute desired target delay based on application constraints. In addition, federal coordinator tracks active devices using the system and permits new devices to enter into the system by guaranteeing that the system capacity strictly satisfies loss and latency requirements.

V. PERFORMANCE EVALUATION

This section presents the performance evaluation of our model for C-TCP over WiFi with dual APs. Table II lists the parameters used in our simulations.

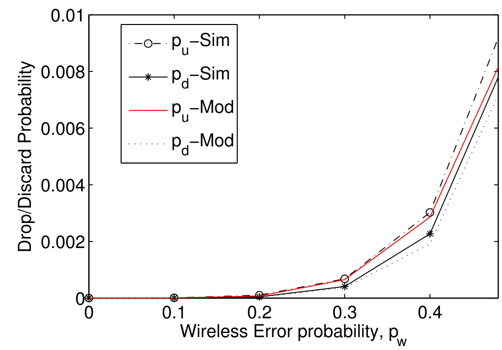

Fig. 3. Discard probability with $N_{u,i}=5$, $N_{d,i}=5$, and $B_{\text{Ap}}=200$.

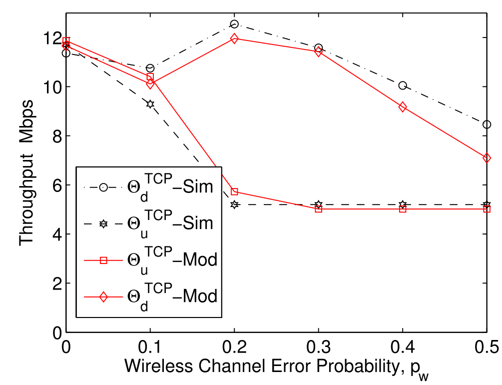

Fig. 4. TCP throughputs with $N_{u,i}=5$, $N_{d,i}=5$, and $B_{\text{Ap}}=200$.

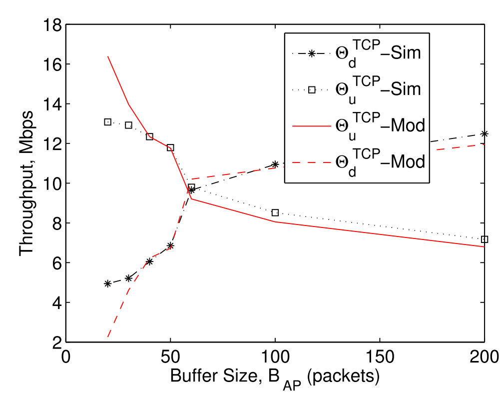

Fig. 5. TCP throughputs with $N_{u,i}=5$, $N_{d,i}=5$, and $p_{w,i}=0.2$.

A. Model Validation

Fig. 3 shows the loss probabilities for uploading and downloading users when transmitting a packet (i.e., dropped or discarded after maximum retransmission attempts) for the case of equal wireless errors perceived by all users. The discard probability increases rapidly with increasing wireless channel errors. The small difference between the discard probabilities observed by the uploading and downloading users is due to the packet size variations of TCP DATA and ACK and the backlogged packets at the AP (AP is always contending). Equations (14) and (15) of the model capture this impact accurately. The TCP throughputs obtained by the uploading and downloading users with the increasing wireless channel errors and buffer overflows are shown in Fig. 4 and Fig. 5, respectively.

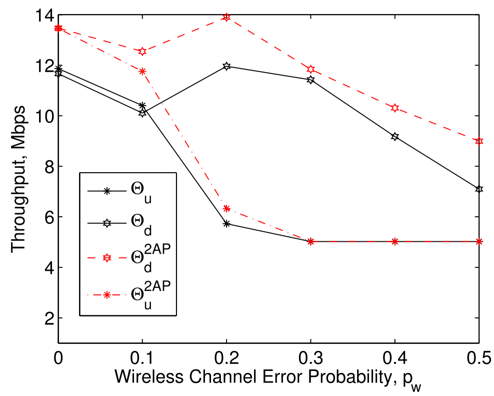

Fig. 6. TCP throughputs without CR $N_{u,i} = 5$, $N_{d,i} = 5$, and $B_{\text{Ap}} = 200$.

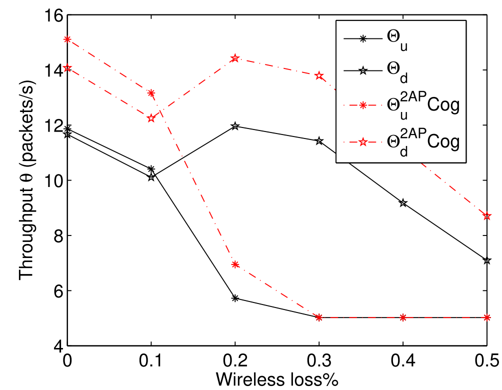

Fig. 8. TCP throughputs with CR $N_{u,i} = 5$ and $N_{d,i} = 5$.

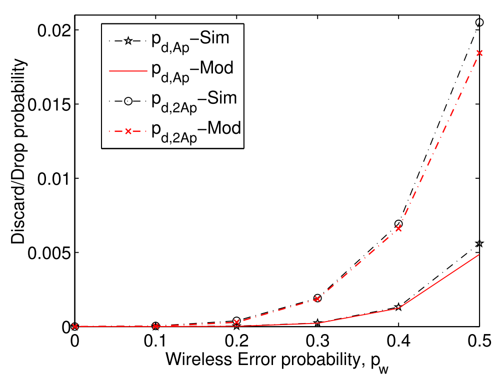

Fig. 7. Discard probabilities with $N_{u,i} = 5$, $N_{d,i} = 5$, and $B_{\text{Ap}} = 200$.

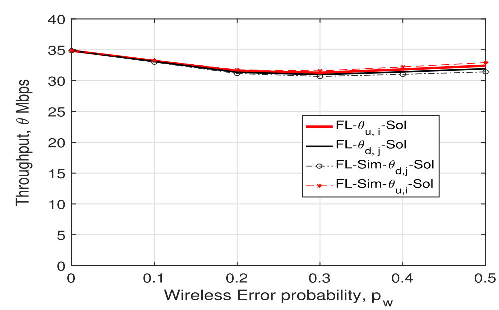

Fig. 9. Fairness solution and TCP throughputs with FL $N_{u,i} = 3$ and $N_{d,i} = 2$.

B. Performance With Dual APs

Fig. 6 illustrates the performance improvement with the dual AP setting. However, the increase in throughput with two APs is not just a simple scaling because of increase in the corresponding transmission losses due to collisions. Moreover, the total throughput of the WiFi system with two APs decreases with the increase in wireless channel errors. Note that for higher channel errors, for example, $p_{w,i} > 0.3$, the throughput obtained with both single and dual APs are almost similar. In particular, it is exactly same for uploads. Fig. 7 shows the corresponding impact of two APs on the discard and loss probabilities.

We also consider an ideal cognitive approach in which the two APs never collide with each other. Fig. 8 shows the corresponding gain in throughput, using the numerical models with (26). There is substantial increase in throughput with the CR techniques, compared to that without CR in Fig. 6. Validating the numerical results for the CR approach requires the development of a new *ns-3* module, which is part of our ongoing work.

Fig. 9 shows results using local and global policy of FL at the APs. By setting h_i^* equal for all STAs/devices in the policy, we can see in Fig. 9 that our proposed FL solves the unfairness problem (shown in Figs. 8 and 5). Under the same network settings of Figs. 7 and 8, but with FL over APs, we conduct an experiment to evaluate our FL approach using both policies. Fig. 9 also signals that with the proposed FL, our proposed system achieves privacy without any loss in performance, which requires further investigations.

VI. Conclusion

In this article, we designed a novel comprehensive analytic model to study the performance of long-lived C-TCP flows over Industry 4.0 WiFi networks while considering the correlated impacts of three types of losses at different layers of the protocol stack. Based on the insights from the developed analytical framework for the case of multiple APs, we compared its performance with the conventional single AP scenario. The insights on throughput fairness, and the applications of FL and CR techniques for the dual AP scenario to further improve C-TCP performance, are novel and interesting for future research. Moreover, the FL and CR frameworks discussed in this article can be implemented in real networks with a software patch at the APs, and were compatible with the existing TCP and WiFi standards.

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Shiva Raj Pokhrel received the B.E. and M.E. degrees in computer engineering from Pokhara University, Pokhara, Nepal, in 2007 and 2013, respectively, and the Ph.D. degree in ICT engineering from Swinburne University of Technology, Melbourne, VIC, Australia, in 2017.

He is currently a Lecturer of Mobile Computing with Deakin University, Geelong, VIC, Australia. From 2017 to 2018, he was a Research Fellow with the University of Melbourne, Melbourne, VIC, Australia (2017–2018) and a Network Engineer with Nepal Telecom, Kathmandu, Nepal, from 2007 to 2014. His current research interests include federated learning, blockchain modeling, optimization, recommender systems, beyond 5G, cloud computing, dynamics control, Internet of Things, and cyber–physical systems as well as their applications in smart manufacturing, autonomous vehicles, and cities.

Dr. Pokhrel was the recipient of the prestigious Marie Skłodowska-Curie Grant Fellowship in 2017.

Surjit Singh received the Graduate degree (with Hons.) in computer science and engineering from Kurukshetra University, Kurukshetra, India, in 2008, the M.Tech. degree (with distinction) in computer science and engineering from Jamia Hamdard (Institute of Eminence), New Delhi, India, in 2012, and the Ph.D. degree in computer science and engineering from National Institute of Technology (NIT) Kurukshetra, Kurukshetra, India, in 2019.

He is currently an Assistant Professor with the Computer Science and Engineering Department, Thapar Institute of Engineering and Technology (TIET), Patiala, India. He was a faculty member with NIT Kurukshetra before joining TIET Patiala. He has authored/coauthored several research papers with the journals of high repute including IEEE Transactions, IET, Elsevier, Springer, Wiley, and Taylor & Francis.

Dr. Singh was a Guest Editor for IEEE Transactions and other journals of high repute.