Length of Optical Fiber Influence on the Performance of Radio-over-fiber Systems

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Abstract

The paper investigates performance impairments due to constraints imposed by the MAC layer when optical fiber is used to extend the IEEE 802.11n network. It is shown that data throughput decreases as fiber length increases. In UDP packet transmission the maximum throughput decreases gradually by 16.6% and 18.6% for basic access and RTS/CTS, respectively. But, with considering TCP packet transmission, the reductions are 21.3% and 22% when the fiber delay increases from 0 to 22.5 µs with using basic mechanism and 0 to 18 µs with RTS/CTS one (i.e., fiber length increases from 0 to 4.3 km and 0 to 3.5 km for basic access and RTS/CTS respectively). It is also noted that the network fails long before physical layer limitations set in due to the timeout values defined within the MAC protocol.

Keywords: *Radio-over-fiber (RoF), WLAN, 802.11n, UDP Transmission, TCP Transmission*

1. Introduction

Radio over fiber is a rather the promising technology for the integration of wireless and wired networks [1]. The main reason for such consideration might be attributed to the possibility of providing services to customers with the two common communication methodologies. The wireless network connection frees the end-users from the constraints of a physical link to the network. Meanwhile optical networks have an almost limitless amount of bandwidth with which to satiate even the most bandwidth hungry customers where bandwidth for wireless networks can be a significant bottleneck. Thus RoF networks offer customers the best of worlds by allowing them to maintain their mobility while also providing them with the bandwidth necessary for both current and future communication/entertainment applications (i.e. Video on Demand, 3DTV, video teleconferencing, etc.) [1]. Furthermore RoF networks provide for greater geographical flexibility as compared to using either one or the other methodologies. Such network topologies may be useful in places such as large buildings, subways and tunnels where such technology is preferable for people roaming with overcoming difficulty of bandwidth limitations and handover issues [1-2].

Figure 1 shows the typical configuration of the wireless local area network (WLAN) based on RoF networks. It consists of four entities: the central site (CS), the optical link, the remote antenna unit (RAU) and the mobile terminal unit (MTU). For the downlink (DL), the WLAN signal modulates the laser at the CS, and the modulated optical signal is sent over the optical link to the RAU. At the RAU, this DL signal is converted back into RF by a photodiode (PD), amplified and sent over the wireless path to the MTU. For the uplink (UL), the WLAN signal from the MTU reaches the antenna at the RAU, is amplified, and modulates the RAU laser. This modulated signal is sent over the optical link to the CS, where it is detected by the CS PD and is transferred to the WLAN AP. The feasibility of the above architecture has been demonstrated using multimode fiber (MMF) [3-4]. It is shown that the fiber length could be in the range of 300 m to a few kilometers [4].

The major issue arises, by deploying optical fiber into the IEEE 802.11 architecture, is the extra delay produced in the system particularly with real time applications [5]. If this delay is too long, then it degrades the overall performance of the system. The key objective is to maintain a stable system in which the MAC layer signaling can be accomplished without any interruption. In this paper the MAC performance of the proposed RoF system is evaluated, in terms of the throughput and the length of the fiber. In addition, an approach by which the maximum limit of the fiber length is pinpointed within a standard 802.11 system.

Considerable efforts have been conducted to investigate such promising system with the achieving significant results [6-8]. However, most of these studies were performed for the IEEE 802.11without taking IEEE 802.11n version as a one of new considered version; also, it did not consider the main mechanisms in the last mile of the wireless part. In addition, length of the backbone optical fiber on the overall system performance did not analyzed for such regard. The fiber length connected to 802.11 WLAN is limited by the mechanism adopted at the terminal. Therefore, these issues will be considered in more details in this study.

The paper is organized as follows: the next section presents the IEEE 802.11 DCF mode within the context of hybrid optical wireless systems. Then, the analytical model is given. It presented for the throughput performance of fiber-fed IEEE 802.11n networks using different MAC mechanisms for Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), in both mechanism basic access and request to sent (RTS)/clear to sent (CTS) mechanism, then the results are illustrated. The conclusions are drawn in the last section.

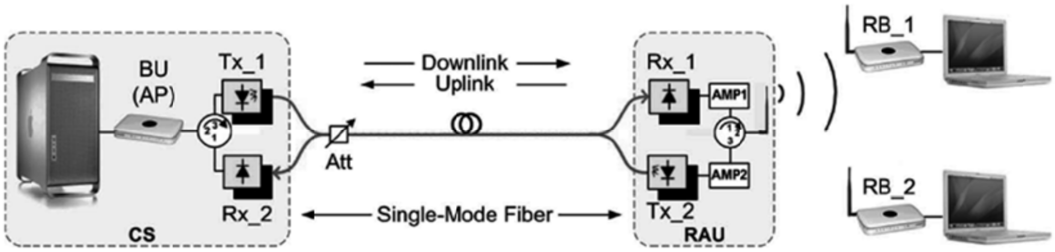


Figure 1. Schematic of optical distributed 802.11(a/b/g/n) broadband networks [6]

2. Access modes of the terminal networks

The terminal accessing network (WLAN) standard IEEE 802.11 [9] - specified a distributed medium access control protocol called Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) as a method of accessing the channel; Retransmission of collided packets is managed according to binary exponential backoff rules [10]. The standard also defined an optional point coordination function (PCF), which is a centralized MAC protocol capable of support collision free and time bounded services. DCF is considered in this study.

DCF describes two techniques to employ for packet transmission. The default scheme is a two-way handshaking technique called basic access mechanism. This mechanism is characterized by acknowledge procedure, after transmitting a frame that requires an ACK response, the source station waits for an ACK Timeout interval; if the ACK response does not occur during this interval, the station concludes that the transmitted frame is failed, and this station will invoke its backoff procedure upon expiration of the ACK Timeout interval.

The alternative choice to the basic access is the four way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS) mechanism has been standardized. Before transmitting a packet, a station operating in RTS/CTS mode "reserves" the channel by sending a special Request-To-Send short frame. The destination station acknowledges the receipt of an RTS frame by sending back a Clear-To-Send frame. After transmitting the RTS frame the source station starts a countdown timer (CTS Timeout), which leaves enough time for the reception of the CTS frame. If the expected response is not received within the CTS Timeout, then the source station assumes that the frame is lost and hence prepares itself for retransmitting the RTS frame. Other stations in the vicinity hearing either an RTS or a CTS or both, defer their transmission by adjusting their network allocation vector (NAV), a timer, to the duration field value of the RTS/CTS frames. If a long fiber path is included in the access point, an extra propagation delay occurs. This may result in the expiration of the (ACK or CTS) Timeout interval before any (ACK, CTS) response arrives at the source station. To overcome this timing impairment, the (ACK, CTS) timeout interval can be incremented so that the station waits a longer period to receive the acknowledgement or CTS fram [4, 6-8, 11].

3. The analytical model

To investigate the maximum fiber length which is incorporated into a standard 802.11n system the analytical model is presented. The TCP and UDP traffic are involved to exchange packets. The basic access and RTS/CTS modes are considered in the analyses of the effect of fiber delay (length) on the performance of fiber lengths. The main parameters values used in the model are given in Table 1, and that not mentioned readers can refer to Ref. [8, 12-13].

The analyses follow the model presented by Bianchi in [14]. The model is modified and extended to consider RoF systems. In addition, effects of ACK and CTS timeouts, as well as, TCP packet transmission over different lengths of fiber are included. To facilitate the comparison purpose the notations used in Ref. [6] are employed.

Table 1. Numerical Parameters

Slot-time (σ)	9 μs
SIFS (Short Inter-frame space	16 μs
DIFS = (2Slot-Time+SIFS)	34 μs
PLCP Preamble & Header	24 μs
MAC Hader & FCS	40 byte
Data rate	144.44 / 300 Mbps
Basic rate	54 Mbps
Control rate	6Mpbs
Payload E [P]	8000 bits
CTS & ACK	14bytes
RTS	20bytes
Air propagation delay (δ)	1 μs
Fiber propagation delay (F)	1 μs=194.8m
W (min Window size)	15
ACK_Timeout or CTS_Timeout	(42.074+2δ) μs

Let the number of associate stations with an AP is n, which are saturated, i.e., they always have a packet ready for transmission. When a transmitted packet from a station encounters a collision with at least one of the n−1 remaining stations in a time slot the probability of unsuccessful receiving (called conditional collision probability) is given as:

$$p = 1 - (1 - \tau)^{n-1} \tag{1}$$

It depends on the probability of a station to transmit a packet in a randomly chosen slot time as:

$$\tau = \frac{1 - p^{m+1}}{1 - p} \,.\, b_{0,0} \tag{2}$$

Where

$$b_{0,0} = \frac{2(1 - 2p)(1 - p)}{(1 - 2p)(W + 1) + pW(1 - (2p)^m)} \tag{3}$$

Let *Th* be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits. To compute *Th*, an analysis for what can happen in a randomly chosen slot time. P_{tr} be the probability that there is at least one transmission in the considered slot time. Since stations contend on the channel, and each transmits with probability τ, then

$$P_{tr} = 1 - (1 - \tau)^n \tag{4}$$

The probability P_s that a transmission occurring on the channel is successful is given by the probability that exactly one station transmits on the channel, conditioned on the fact that at least one station transmits, i.e.

$$P_s = \frac{n\tau \,.\, (1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau \,.\, (1-\tau)^{n-1}}{1-(1-\tau)^{n}} \tag{5}$$

Thus, the throughput can be calculated as:

$$Th = \frac{P_s \,.\, P_{tr} \,.\, E_{[Packet]}}{(1-P_{tr}).\sigma + P_s \,.\, P_{tr}.\, T_{success}^{Operational_{mode}} + (1-P_s)\,.\, P_{tr} \,.\, T_{Failur}^{Operational_{mode}}} \tag{6}$$

The average of data packet payload size in bits is $E_{[Packet]}$. A successful transmission in a Slot Time occurs with the probability of $P_s P_{tr}$. The average time the wireless channel is sensed busy because of a successful transmission $T_{success}^{Operational\_mode}$ and because of an unsuccessful transmission $T_{Failur}^{Operational\_mode}$ depends on the operational mode, i.e., the mechanism and the type of packet traffic used by the system.

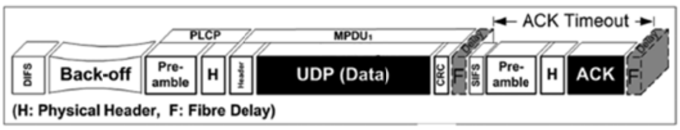
If the basic access method is used over the fiber, illustrated in Fig.2, the following equations are obtained:

$$T_{success}^{UDP-bassic} = \{DIFS + 2(T_{PLCP} + F + \delta) + T_{ACK} + SIFS + T_{DATA}\} \tag{7}$$

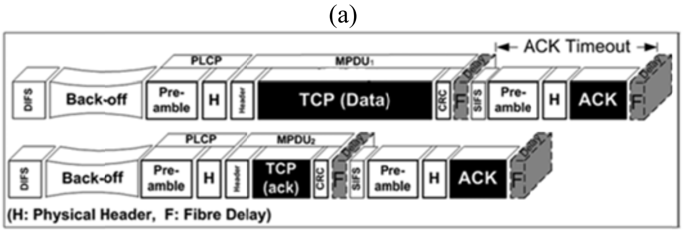
$$T_{Failure}^{UDP-bassic} = \{DIFS + T_{PLCP} + ACK_{Timeout} + 2F + T_{DATA}\} \tag{8}$$

$$\begin{aligned} T_{success}^{TCP-bassic} &= \{2(T_{PLCP} + F + \delta) + DIFS + T_{ACK} + SIFS + T_{DATA} + T_{ACK}^{TCP} \\ &< 2(T_{PLCP} + F + \delta) + DIFS + T_{ACK} + SIFS + T_{DATA} >\} \end{aligned} \tag{9}$$

$$T_{Failure}^{TCP-bassic} = T_{Failure}^{UDP-bassic} \tag{10}$$



(a)



(b)

Figure 2. Packet exchange of basic access method when UDP and TCP traffic is used within a hybrid optical-wireless 802.11 networks. (a) UDP traffic over basic access mechanism. (b) TCP traffic over basic access mechanism [6].

Figure 3 depicts the case of employing the RTS/CTS mode and the following equations obtained:

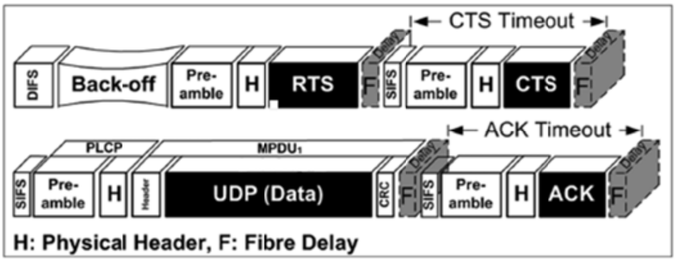
$$T_{success}^{UDP-RTS} = \{DIFS + 4(T_{PLCP} + F + \delta) + T_{RTS} + T_{CTS} + T_{ACK} + 3SIFS + T_{DATA}\} \tag{11}$$

$$T_{Failure}^{UDP-RTS} = \{DIFS + T_{PLCP} + T_{RTS} + CTS_{Timeout} + 2F\} \tag{12}$$

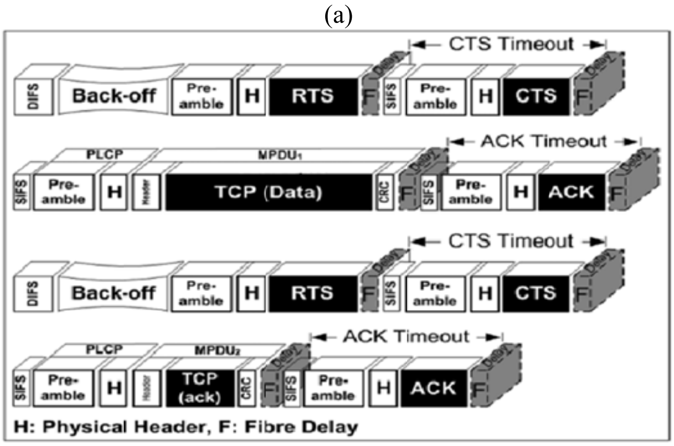
$$T_{success}^{TCP-RTS} = \{4(T_{PLCP} + F + \delta) + DIFS + T_{RTS} + T_{CTS} + T_{ACK} + 3SIFS + T_{DATA} + T_{ACK}^{TCP}. < DIFS + 4(T_{PLCP} + F + \delta) + T_{RTS} + T_{CTS} + T_{ACK} + 3SIFS + T_{DATA} > \} \quad (13)$$

$$T_{Failure}^{TCP-RTS} = T_{Failure}^{UDP-RTS} \quad (14)$$

Where $\mathrm{T}_{\mathrm{ACK}}^{\mathrm{TCP}}$ is the probability of a TCP acknowledgement packet transmission, which is dependent on the TCP protocol. For example, if each two TCP data packets are acknowledged by only one TCP ack frame, then $\mathrm{T}_{\mathrm{ACK}}^{\mathrm{TCP}} = 0.5$. For the case, where all TCP data frames are acknowledged at the TCP layer $\mathrm{T}_{\mathrm{ACK}}^{\mathrm{TCP}} = 1$.



(a)



(b)

Figure 3. Packet exchange of RTS/CTS method when UDP and TCP traffic is used within a hybrid optical-wireless 802.11 networks. (a) UDP traffic over RTS/CTS mechanism. (b) TCP traffic over RTS/CTS mechanism [6].

4. Analyses of the achieved results

The model presented in the previous section is used to investigate the maximum fiber length which could be incorporated into a standard 802.11n system where TCP and UDP traffic are involved. In both mechanisms with wireless network, namely, basic access and RTS/CTS mechanism, the system performance is analyzed. Fig. 4 shows that the maximum throughput decreases gradually by 16.6% and 18.6% for basic access and RTS/CTS, respectively, with employing UDP. On the other hand with utilizing TCP, the respective reductions are 21.3% and 22% for basic access and RTS/CTS, respectively, when the fiber delay increases from 0 to 22.5 µs and 0 to 18 µs (i.e., fiber length increases from 0 to 4.3 km and 0 to 3.5 km for basic access and RTS/CTS respectively As the system round-trip delay reaches the ACK Timeout value the performance falls abruptly. The throughput sharply decreases when the ACK Timeout expires. Since the ACK Timeout (87.074µs) is greater than the CTS Timeout value (78.074µs) the cutoff in the throughput of the RTS/CTS method occurs earlier than the basic access method. This timeout values is more than timeout values defined in the IEEE 802.11

(Timeout ACK, CTS = (SIFS +TPLCP +TACK +Slot Time). Increasing the timeout allows the system to wait longer in order to receive the acknowledgement packet (i.e. CTS or ACK) and will also have an effect on the total throughput of the connection. This assumption is also used in both of [4] [6-8] and [11].

For comparison purpose Fig. 5 and Fig. 6 are given to show the relationship between throughput versus fiber delay with different payload and data rate. Where Fig.5 study the effect different payload size (2000, 8000) bits, on throughput, where the expected throughput increase as the payload size in the network increases. Fig.6 investigates the same relationship but for different data rates (R=144.4 Mbps represented by dotted lines and R=300 Mbps represented by solid lines). The transmission rate increases with the throughout. This is due to the time spent for packet transmission decreases as the data rate increases.

Figure 7 shows the throughput versus the load in the network for frame sizes distributed uniformly in the range of [1000, 8000] bits, for two different fiber delays: 5.133μs and 22.3 μs (i.e. 1 km and 4.3 km, respectively), and two different access modes; the basic access and RTS/CTS, in UDP and TCP. The results show that using UDP gives the better performance in the long fiber and when longer frames are used, in both mechanism modes.

5. Conclusions

In this paper the performance of IEEE 802.11n is analyzed for RoF network. The achieved results demonstrating that the maximum length of fiber might be deployed for 802.11n systems. It constrained by ACK, RTS timeout value defined in the IEEE 802.11n standard. Extending the ACK Timeout value to a 87.074μs enabled the maximum fiber length to go up to 4.3km, and increasing the CTS timeout value to 78.074μs, the length of the fiber is raised to 3.5 km. It is also shown that realizing the throughput with RTS/CTS mode is lower than that with adopting the Basic Access method for both protocols, namely, TCP and UDP, due to the involvement of more overhead packets. Finally, the analyses shown that there is a tradeoff between the throughput and the length of the fiber.

6. References

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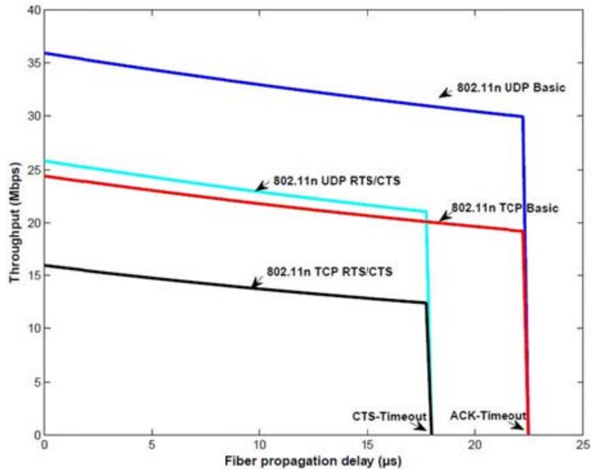

Fig 4. Variation of throughput with fiber delay for TCP and UDP traffic when the basic access and RTS/CTS method is used.

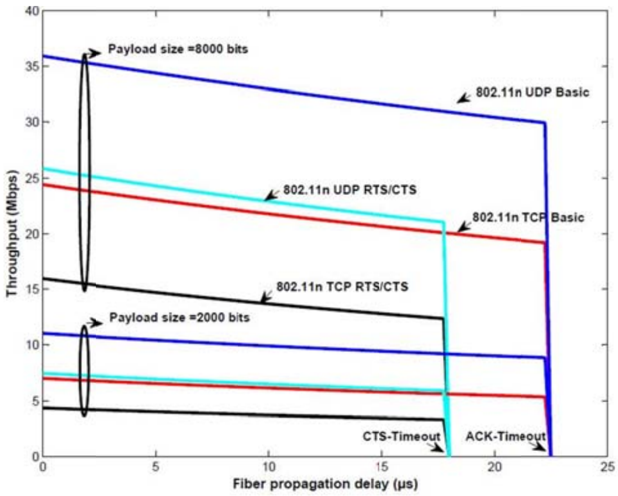

Fig 5. Variation of throughput with fiber delay for TCP and UDP traffic when the basic access and RTS/CTS method is used for different payload size, (2000, 8000) bits.

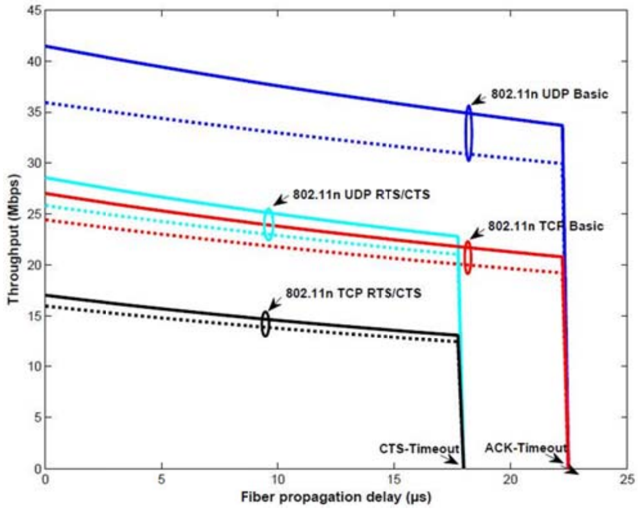

Fig 6. Variation of throughput with fiber delay for TCP and UDP traffic when the basic access and RTS/CTS method is used for different data rate, R=144.44Mbps (represented by dotted line), R=300Mbps (represented by solid line).

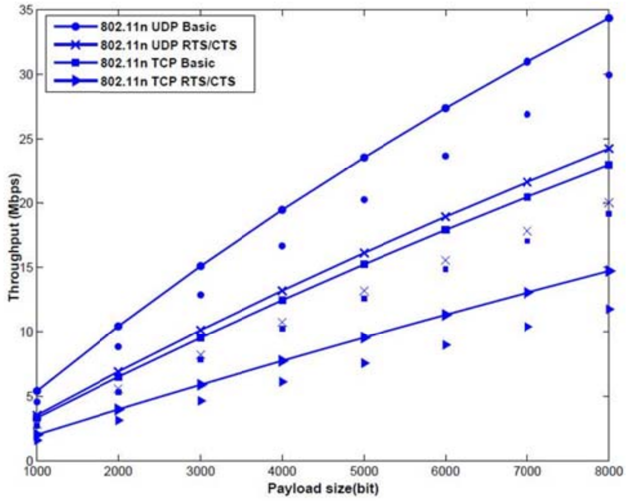

Fig 7. Effect of the network load on throughput for different access modes and two fiber delays 5.133µs, 22.3µs. (fiber delay=5.133µs represented by lines and fiber delay=22.3 represented by symbols).