Protocol Parameter Selection for Fiber-Supported IEEE 802.16m Networks

Pavlos Sklikas, *Member, IEEE*, Majlinda Mjeku, *Member, IEEE*, and Nathan J. Gomes, *Senior Member, IEEE*
Broadband and Wireless Communications Group
University of Kent
Canterbury, United Kingdom
P.P.Sklikas@kent.ac.uk

***Abstract*—In this paper we investigate protocol issues that might arise due to the extra fiber propagation delay in fiber-fed IEEE 802.16m networks. Our study indicates that although the fiber delay might affect network performance, an informed choice of protocol parameters, such as the guard times and the ranging channel structure, can minimize the reduction in efficiency and allow for relaxation of some of the constraints imposed on the optical distribution network architecture.**

Keywords—Radio-over-fiber (RoF), Medium Access Control (MAC), OFDMA, IEEE 802.16m.

I. Introduction

Radio-over-fiber (RoF) techniques enable the distribution of RF modulated light signals from a central location (i.e. an Advanced Base Station - ABS), where all the signal processing is located, to remote antenna units (RAUs) via an optical distribution network. The main function in the RAUs is optoelectronic conversion of the signal. The optical distribution is transparent to the signal modulation or coding used, however it adds an extra propagation delay, which might interfere with the timing limitations of the protocol operations defined, and might affect their performance.

In this paper, we investigate for the first time protocol issues that arise due to the fiber propagation delay in fiber-fed time division duplex (TDD) 802.16m networks. IEEE 802.16m, an amendment to IEEE 802.16e [1], is a fourth generation radio access technology candidate in the International Mobile Telecommunications Advanced program. Thus, as an extension to our study on fiber propagation delay effects on IEEE 802.16e RoF networks [2], this paper presents the limitations and performance of 802.16m RoF networks.

The main features of 802.16m relevant to our study are given in Section II. The main mechanisms of the 802.16m protocols which deal with the propagation delay, the constraints they put on the optical distribution network and their adaptation required in order to preserve correct protocol operation in the presence of fiber delay are presented in Sections III, IV and V. A mathematical analysis of the fiber delay effect on the system's Medium Access Control (MAC) data rate performance is also given in Section III. Conclusions are drawn in Section VI.

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II. IEEE 802.16m

In this section we briefly introduce the main features of the IEEE 802.16m physical (PHY) and MAC layers, concentrating on those relevant to our study. IEEE 802.16m uses orthogonal frequency-division multiple access (OFDMA) in the uplink (UL) and downlink (DL), supporting both TDD and frequency-division duplex (FDD) modes. The OFDMA symbol time structure comprises the useful symbol time T_b, preceded by the cyclic prefix (CP), which is a copy of the last portion of the useful symbol period (of a duration equal to T_g), used to collect multipath signals and maintain orthogonality of the subcarriers. 802.16m defines a 20 ms superframe, divided into four 5ms frames, as shown in Fig. 1 for the case of TDD operation. The 5ms frames are further divided into a number of subframes where each of these comprises an integer number of OFDMA symbols. There are four types of subframe, referred to as Type-1, Type-2, Type-3, and Type-4, consisting of six, seven, five, and nine OFDMA symbols respectively. Subframes are assigned adaptively for either DL or UL transmission, based on the capacity needs of each direction. The DL to UL (DL:UL) subframe ratios supported are: (8,0), (6,2), (5,3), (5,2), (4,4), (4,3), (4,2), (3,5), (3,4), (3,3), (3,2), (2,4) and (2,3) where the first number in each pair represents the number of DL subframes and the second number represents the number of UL subframes per frame. There are two switching points in each frame, referred to as the transmit to receive transition gap (*TTG*) and receive to transmit transition gap (*RTG*), to allow for the change of directionality during transmission/reception. The 802.16m superframe begins with the superframe header (SFH) and it also contains preambles for DL synchronization.

The 802.16m MAC is connection oriented, with the bandwidth requested by the Advanced Mobile Station (AMS) on a per-connection basis. The start and end times of the AMS's grants and the details of the allocations (e.g. modulation and coding to be used) are broadcast by the ABS via the Advanced-Medium Access Protocol (A-MAP) messages. The A-MAP occupies resources in all DL subframes and consists of both non-user specific control information (i.e. information intended for all users) and of user-specific information. Moreover, each MAC Protocol Data Unit (PDU) begins with a MAC header, generic or compact depending on the type of connection, and may be followed by one or more extended headers.

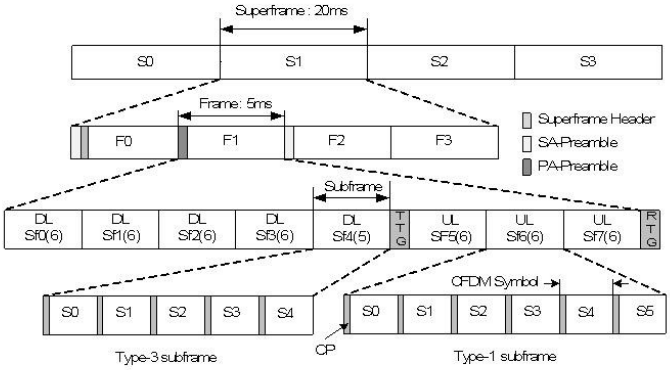

Fig. 1. Example of IEEE 802.16m TDD frame structure.

III. DL-UL Timing in Presence of Fiber Delay

In order to provide for the DL-UL timing synchronization, 802.16m defines guard times (*GT*) between the DL and UL subframes, comprising the *TTG,* accounting for the cell's maximum round-trip delay plus the time needed at the AMS for the DL to UL transition (T_{AMS}^{RxTx}), and the *RTG* accounting for the time needed for the UL to DL transition at the ABS (T_{ABS}^{RxTx}). While the timing advance mechanism is used to account for round-trip delay, in a RoF network it also needs to account for the presence of the optical distribution links. 802.16m, however, defines fixed *TTG*/*RTG* values for different bandwidths and CP durations [3]. In order to accommodate long fiber distribution links with minimum efficiency loss, *GT* needs to flexibly depend on the maximum optical propagation delay D_{max} expected, as shown by (1):

$$GT = TTG + RTG = 2D_{\max} + T_{AMS}^{R_xT_x} + T_{ABS}^{R_xT_x} \tag{1}$$

Table I presents the *TTG*/*RTG* default durations and the maximum fiber length for RoF (L_{max}) and cell radii for non-RoF (C_{max}) systems for various channel bandwidths and CP durations. L_{max} and C_{max} values are obtained using (1) and assuming the maximum value of T_{AMS}^{RxTx} = 50 µs [3]. Knowing the guard time needed for a particular fiber delay, we will now evaluate its influence on the efficiency of the superframe and its effects on the MAC data rate (MDR). Definitions and values for parameters used in the following analysis can be found in Table II.

A. *Effect of Fiber Delay on the Superframe Efficiency*

In the following analysis we link the RoF cell's maximum size to the fiber length; however, in practice the real cell size could be several times smaller as the fiber will not be laid in a straight line. The wireless propagation delay is considered negligible compared to fiber propagation delay as the coverage area of each RAU is assumed small.

It is clear that for correct protocol operation any increase in the cell sizes, be it a normal (non-RoF) or a RoF 802.16m network, would require adaptation of the gaps, resulting in a reduction of the superframe efficiency, C_{spf_r}, which (for a given frame duration T_f) can be calculated as:

$$C_{spf\_r} = \frac{2D_{\max}}{T_f} \tag{2}$$

In an OFDMA system, the time allocation to *GT* within a frame will be performed in multiples of the OFDM symbol duration, plus any frame time left unallocated for transmission due to it being less than the OFDM symbol duration. The number of OFDM symbols, N_{GT_sym}, that need to be allocated to *GT* for a specific cell radius (fiber length), $L_{cell\text{-}max}$ in order to maintain DL-UL synchronization can be calculated as:

TABLE I. 802.16m Default TTG/RTG and Maximum Cell Sizes

CP	BW (MHz)	TTG+RTG (µs)	TTG (µs)	RTG (µs)	C_{max} (km)	L_{max} (km)
1/8	5/10/20	165.714	105.714	60	8.357	5.763
	5/10/20	268.571	208.571	60	23.785	16.403
	5/10/20	371.428	311.428	60	39.214	27.044
	8.75	161.6	87.2	74.4	5.580	3.848
	7	248	188	60	20.7	14.275
1/16	5/10/20	142.853	82.853	60	4.927	3.398
	5/10/20	239.996	179.996	60	19.499	13.447
	5/10/20	335.139	275.139	60	33.77	23.29
	8.75	212.8	138.4	74.4	13.26	9.144
	7	240	180	60	19.5	13.448
1/4	5/10/20	199.998	139.998	60	13.499	9.31
	8.75	264	189.6	74.4	20.94	14.441
	7	200	140	60	13.5	9.31

TABLE II. PHY/MAC Parameters

Parameter	Comment	Value
BW	Channel Bandwidth	10 MHz
N_{FFT}	FFT size	1024
Δf	Subcarrier spacing	10.9375 kHz
G	Cyclic Prefix ratio	1/8
T_g	Cyclic prefix time	11.4286 µs
T_b	Useful symbol time	91.4286 µs
T_s	Symbol time	102.857 µs
T_f	Frame duration	5 ms
T_{spf}	Superframe duration	20 ms
n_f	Refractive index of fiber	1.5
N_{used}	Number of active (used) subcarriers	865
N_{pilot}	Number of pilot subcarriers	108
$TTG+RTG$	Default GT assignment	165.714 µs
$S_{ct\text{-}MAP}$	Non user specific part of A-MAP	12 bits
$S_{ass\text{-}IE}$	Assignment information element	48 subcarriers
SFH	Superframe header	1152 subcarriers
$AGMH$	Advanced Generic MAC Header	16 bits

$$N_{GT\_sym} = \left\lceil \frac{2n_f L_{cell-\max}}{T_s c} \right\rceil \quad (3)$$

where, $\lceil x \rceil$ gives the closest integer not less than x, n_f represents the refractive index of fiber and c the speed of light. The symbol time T_s is given in Table III, which presents the 802.16m OFDMA parameters for TDD mode, for the various channel bandwidths and CP durations. Fig. 2 shows the number of OFDM symbols that need to be allocated to GT in order to accommodate a certain cell radius/fiber length, for a 5/10/20 MHz system. It can be seen from Fig. 2 that each allocated OFDM symbol can serve up to 10.2 km of fiber in a RoF network, whereas it will provide for a coverage extension of up to 15.4 km in a normal 802.16m network. These values do not take into account T_{AMS}^{RxTx} (i.e. ≤ 50 μs [3]).

TABLE III. 802.16M OFDMA PARAMETERS FOR TDD

	Channel bandwidth BW (MHz)	5	7	8.75	10	20
	FFT size (N_{FFT})	512	1024	1024	1024	2048
	Sampling frequency F_s (MHz)	5.6	8	10	11.2	22.4
	Useful symbol time T_b (μs)	91.428	128	102.4	91.428	91.428
CP 1/8	**CP time T_g (μs)**	11.428	16	12.8	11.428	11.428
	Symbol time T_s (μs)	102.857	144	115.2	102.857	102.857
	Data OFDM symbols/5 ms	47	33	42	47	47
CP 1/16	**CP time T_g (μs)**	5.714	8	6.4	5.714	5.714
	Symbol time T_s (μs)	97.143	136	108.8	97.143	97.143
	Data OFDM symbols/5 ms	50	35	44	50	50
CP 1/4	**CP time T_g (μs)**	22.857	32	25.6	22.857	22.857
	Symbol time T_s (μs)	114.286	160	128	114.286	114.286
	Data OFDM Symbols/5 ms	42	30	37	42	42

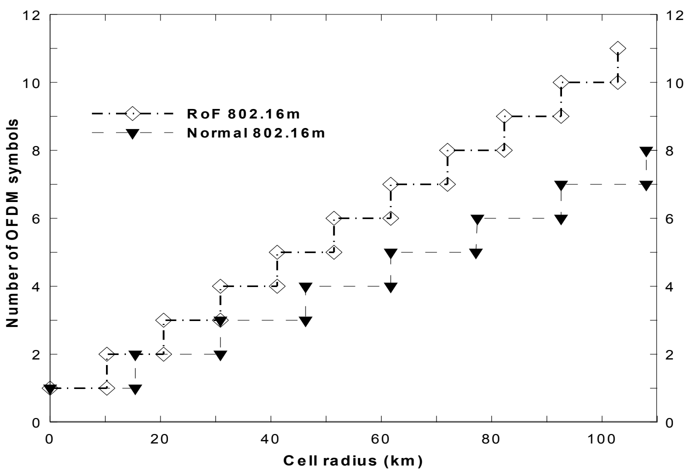

Fig. 2. Guard time allocation vs. maximum cell size.

B. *Effect of Delay on MAC Data Rate (MDR)*

This subsection evaluates the effects on MAC layer efficiency of an increase in the total propagation delay of the system due to the extra fiber propagation delay, while maintaining DL-UL timing. The MAC layer throughput S, is defined as the average number of data bits transferred by the MAC layer in unit time and can be adapted from [4] as:

$$S = \rho \frac{\sum_{n=1}^{4} (N_{bits_n} - OH_n)}{T_{spf}} \quad (4)$$

where n represents each frame of the superframe, N_{bits_n} represents the total number of transmitted bits per frame, OH_n represents the overhead bits per frame and T_{spf} the duration of the superframe; ρ is a factor which accounts for the MAC PDU header. In our analysis the MDR is obtained for ρ=1, i.e. by not accounting for the MAC PDU header, while only the DL MDR is evaluated. Some throughput analysis has also been done (not reported) showing minimal effect of the MAC PDU size. We assume that the assignment of resources to the different AMSs is performed in terms of subcarriers.

Based on [4], the number of subcarriers N_{dsc} needed for the transmission of a MAC PDU, L_{PDU} bits long, is given by (5):

$$N_{dsc} = \frac{L_{PDU} N_R}{B_{sc} C_r} \quad (5)$$

where B_{sc} represents the number of bits per subcarrier and depends on the modulation type, C_r represents the coding rate and N_R the repetition coding. The available data subcarriers in the DL, N_{DL_dsc} in each of the frames can be calculated as:

$$N_{DL\_dsc} = K_{DL} N_{SYM} N_{dsc\_sym} \quad (6)$$

where K_{DL} represents the proportion of symbols of the frame used for DL transmission and N_{dsc_sym} represents the number of data subcarriers per symbol. For $\lfloor x \rfloor$ giving the closest integer not greater than x, the number of symbols available for data transmission per frame, N_{SYM}, is calculated by (7):

$$N_{SYM} = \left\lfloor \frac{T_f - GT}{T_s} \right\rfloor \quad (7)$$

For the calculation of DL overheads, we consider the SFH, modulated using QPSK with a 1/16 coding rate, comprising preambles occupying two OFDM symbols, and the A-MAP, transmitted using QPSK with 1/2 coding rate. The number of bits occupied by the A-MAP, N_{MAP} can be calculated as [3]:

$$N_{MAP} = N_{DL\_Sfr} S_{ct-MAP} + N_{AMS} S_{ass-IE} \quad (8)$$

where N_{DL_Sfr} represents the number of DL subframes per frame, $S_{ct\text{-}MAP}$ is the size of the non-user-specific part of the A-MAP, N_{AMS} represents the number of AMSs in the network and $S_{ass\text{-}IE}$ is the size of one A-MAP Information Element (IE).

C. Results

The superframe structure considered in our analysis is that of Fig. 1 where the DL is a combination of Type-1 and Type-3 subframes [3] with a (4,4) DL:UL subframe ratio. We assume that $T_{AMS}^{RxTx} = 30$ μs, while the *RTG* is kept fixed at 60 μs [3]. In our analysis any increase of the *TTG* results in an equal decrease of the superframe time allocated to the DL transmissions, resulting in different combinations of DL subframe types, as shown in Table IV.

Fig. 3 shows the results of our analysis for the MDR of an 802.16m RoF network as a function of fiber delay for 5 different numbers of AMSs, when the modulation employed is QPSK 1/2. There is a drop in MDR, shown by step decrements in the figure, whenever the time allocated to *TTG* is increased by 1 OFDM symbol. The drop in the MDR is more significant for longer fiber lengths. The total MDR of the system decreases with an increase in the number of AMSs operating in the network, due to more overhead required for their transmissions. Note that the results assume an ideal channel so when the transmission distance increases only the effects of fiber delay are shown.

MDR results for the scenario of an increasing number of AMSs which employ higher level modulation (i.e. 64QAM 5/6 and 16QAM 3/4) are shown in Fig. 4 for a range of fiber lengths. These indicate a uniform decrease in MDR regardless of the number of AMSs operating in the network. Results in Figs. 4 and 5 show that increasing the DL:UL ratio on demand will decrease the detrimental effects of fiber delay and lead to an increase in DL MDR, regardless of the fiber delay and the number of stations. Fig. 5 plots the MDR decrease relative to the default transition gap duration case (defined in 802.16m), calculated as $(MDR_{non\_RoF} - MDR_{RoF}) / MDR_{non\_RoF}$, as a function of AMSs for two different fiber delays and three subframe ratios, i.e. (4,4), (5,3), (6,2), in consideration. From Fig. 5 it can be seen that the MDR decrease contributed by the extra fiber delay is lower for the more favorable DL ratios. For example, for fiber lengths up to 17.5 km and 38.1 km there is respectively a 5% and 14% MDR decrease when 10 AMSs operate in the network for the ratio (4,4); the MDR decreases by only 3% and 9%, respectively when the DL:UL ratio changes to (6,2). The effect is more significant for longer fiber delays and for higher number of operating AMSs; the relative influence of fiber delay on the total DL MDR and the extra

TABLE IV. COMBINATION OF DL SUBFRAME TYPES VS. GUARD TIMES

GT (μs)	Nr of DL subframes Type-1	Nr of DL subframes Type-3	Nr of DL symbols
165.714	4	0	24
268.571	3	1	23
371.428	2	2	22
474.285	1	3	21
577.142	0	4	20
679.999	N/A	N/A	19

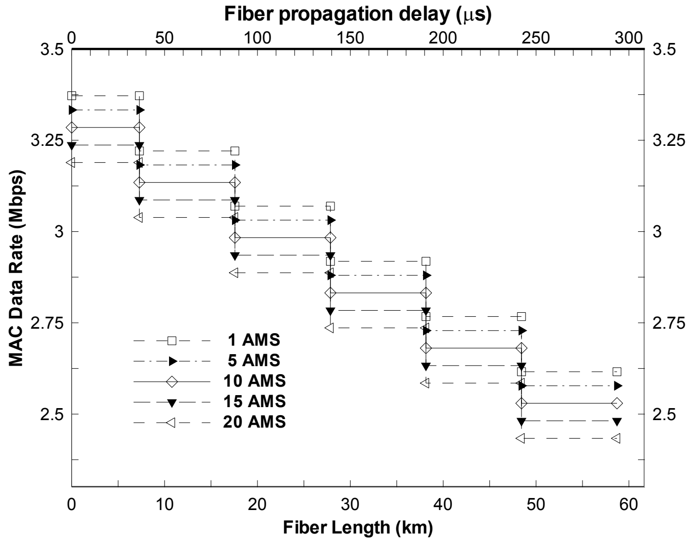

Fig. 3. Variation of MAC Data Rate with fiber length for QPSK 1/2.

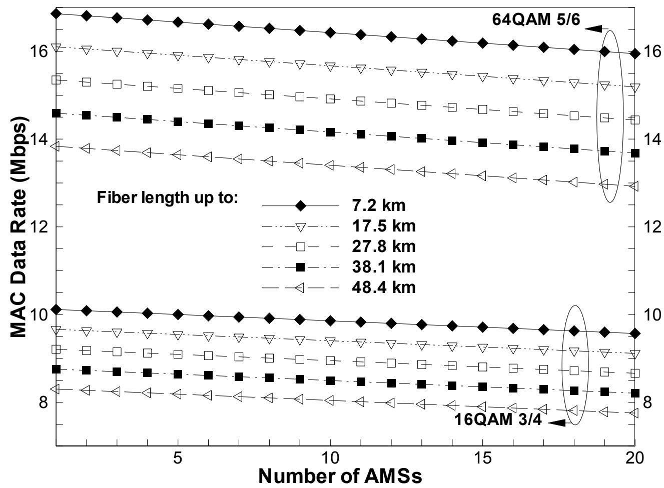

Fig. 4. Variation of MAC Data Rate with the number of AMSs for 64QAM 5/6 and 16QAM 3/4.

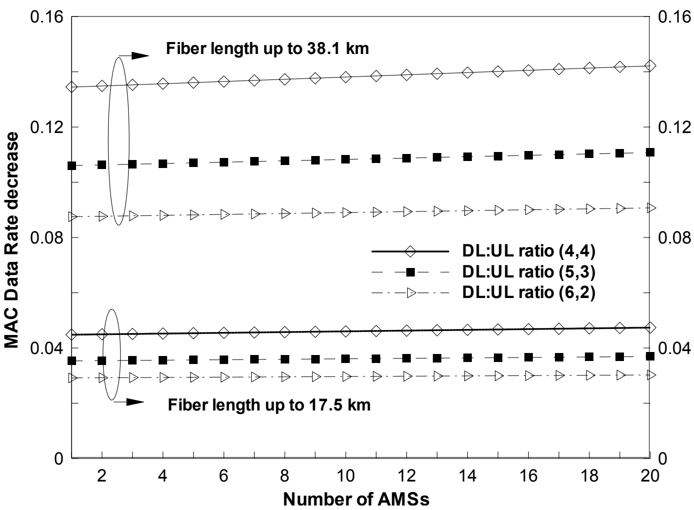

Fig. 5. MAC data rate decrease as a function of the number of the AMS.

overheads incurred when the number of AMSs increases become less significant when the number of available DL OFDM symbols increases. The more favorable DL ratios will, however, affect the UL performance; this is not considered a major problem due to the greater traffic demands usually imposed on the DL.

IV. Ranging and Limitations to the Cell Size

The ranging procedure is used to estimate the propagation delay of the transmitting stations and determine their timing advance. In a RoF 802.16m network, the ranging procedure would be expected to estimate the total propagation delay (i.e. both air and fiber propagation delay) and thereby achieve correct synchronization at the receiver; however, as we investigate in this section, for successful ranging the maximum fiber lengths might need to be constrained.

The initial ranging transmission involves transmission of a ranging code, selected randomly from a domain of initial ranging codes, during a ranging slot using a random backoff. The ABS is able to detect and identify these ranging codes and extract timing information for each AMS. The ranging process is iterative, where each AMS adjusts its timing according to the instructions received by the ABS, until it is successful.

As shown in Fig. 6, the IEEE 802.16m ranging channel consists of three parts: the ranging cyclic prefix (RCP), the ranging preamble (RP) and the guard time (GT), whose lengths we denote as T_{RCP}, T_{RP} and T_{GT} respectively. In order to be able to estimate the timing offset during the ranging procedure while avoiding intersubcarrier and intersymbol interference with the next OFDMA symbol, the following conditions need to be satisfied [6]:

$$\begin{aligned} T_{RP} &\geq 2D_{max} + \sigma \\ T_{RCP} &\geq 2D_{max} + \sigma \\ T_{GT} &\geq 2D_{max} \end{aligned} \tag{9}$$

where σ is the delay spread of the channel. It is clear from these conditions that the maximum cell size is constrained by T_{RCP}, T_{RP} and T_{GT}. Due to the slower signal propagation in fiber, the maximum fiber length of the RoF 802.16m network supported by the ranging procedure will be smaller than the cell size of its non-RoF 802.16m counterpart.

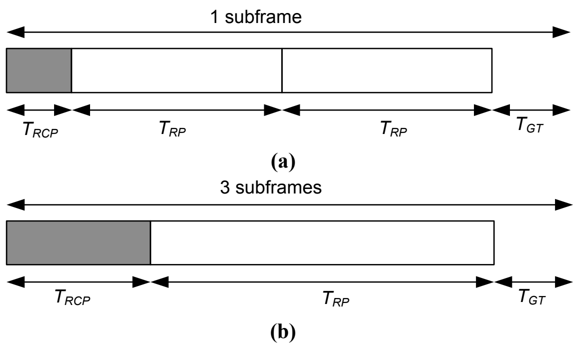

Fig. 6. Ranging channel structure (a) Format 0, (b) Format 1.

In order to support different cell sizes, the 802.16m defines two different ranging channel formats, allocated in one and three subframes, respectively, whose structures are shown in Fig. 6a and Fig. 6b, while their parameters are shown in Table V. The parameters depend on T_g and T_b. Format 0 parameters also depend on k_1 and k_2 which are calculated as:

$$k_1 = \frac{N_{sym\_s} + 1}{2}; \quad k_2 = \frac{N_{sym\_s} - 4}{2} \tag{10}$$

where N_{sym_s} refers to the number of OFDMA symbols in a subframe. According to Fig. 6 and Table V, ranging channel Format 0 occupies one subframe; because we assume that the ranging channel always starts in the first UL subframe [3], and based on the various DL:UL ratio and subframe type configurations defined in [3], Format 0 always uses a Type-1 subframe (i.e. a subframe of 6 OFDMA symbols). Thus, based on (10) and Table V, T_{RCP} duration for Format 0 can be re-written as $3.5T_g + T_b$.

Table VI compares the coverage range of the ranging procedure in a normal 802.16m C_{max_IR} versus the maximum fiber length L_{max_IR} that can be inserted, for both ranging formats conforming to the design criteria given in (9), for 5/10/20 MHz channel bandwidths and the different DL:UL ratio and subframe type configurations defined in [3]. It can be seen from the results that the range covered by the ranging procedure depends greatly on the chosen parameters and it could cover up to 62 km of fiber. The results do not take into account the delay spread, assumed to be negligible in fiber. A similar calculation for 7 and 8.75 MHz channel bandwidths (not presented here) results in a maximum fiber length of 93 km (for 7 MHz bandwidth, Format 1 and a CP equal to 1/8).

TABLE V. Ranging Channel Formats and Parameters

Format	T_{RCP}	T_{RP}	Δf_{RP}	Subframes occupied
0	$k_1T_g + k_2T_b$	$2T_b$	$\Delta f/2$	1
1	$3.5T_g + 7T_b$	$8T_b$	$\Delta f/8$	3

TABLE VI. Ranging Channel Formats and Coverage Range

CP	Format	Subframe type(s)	T_{RCP} (µs)	T_{RP} (µs)	T_{GT} (µs)	C_{max_IR} (km)	L_{max_IR} (km)
1/8	0	Type-1	131.4	182.8	119.9	17.9	12.4
	1	3 × Type-1	680	731.4	439.9	65.9	45.5
1/16	0	Type-1	111.4	182.8	105.7	15.8	10.9
	1	2 × Type-1 and 1 × Type-2	660	731.4	454.2	68.1	46.9
		3 × Type-1	660	731.4	357.1	53.5	36.9
1/4	0	Type-1	171.4	182.8	148.5	22.2	15.3
	1	3 × Type-1	720	731.4	605.7	90.8	62.6

V. ISI CAUSED BY THE FIBER DISTRIBUTION NETWORK

A problem that could arise in a RoF 802.16m scenario is that of Inter-Symbol Interference (ISI) caused by the optical distribution network using fibers of different lengths for the distribution of the signal from the ABS to different RAUs. The AMSs will most probably receive different replicas of the same signal being transmitted via different RAUs with a delay difference, T_d, corresponding to the difference in the fiber lengths used to connect each RAU to the ABS.

In a RoF 802.16m scenario, the OFDMA symbol's CP, introduced to collect the wireless propagation multipath, could similarly serve to counteract the ISI problem caused by the optical distribution network; the OFDMA signal will be insensitive to the difference in the fiber lengths to different RAUs as long as the CP is longer than this delay difference. It is useful therefore to determine the maximum difference in fiber lengths (i.e. Δ_{Lmax}) that the CP could cover. The 802.16m is designed to support three different CP ratios, i.e. 1/16, 1/8 and 1/4. In order to prevent ISI due to the signal travelling via optical fibers of different lengths, the following condition, adapted from [5] and [7] so that it includes the influence of the optical propagation, needs to be satisfied:

$$T_g \geq T_{d-\max} + \sigma_w \tag{11}$$

where σ_w is the delay spread of the wireless channel and T_{d_max} is the maximum delay spread of fibers.

Practically the CP has to be either 2-4 times the maximum anticipated delay-spread or kept to 25% of T_b [8]. The authors of both [9] and [10] have used a guard time duration of two and three times, respectively, the propagation delay corresponding to the difference in fiber lengths between the RAUs. For our calculations we assume that CP has to be three times the maximum delay spread; Table VII shows the theoretical maximum differences in fiber lengths that each CP could support for different channel bandwidths, assuming a negligible wireless delay spread. For 10 MHz bandwidth for example the fibers used could differ in length by 0.394 km, 0.788 km, and 1.576 km for CP ratios 1/16, 1/8, and 1/4, respectively. Employing a CP of 1/4, however, in order to account for larger fiber delay differences, will increase the overhead, resulting in a loss of efficiency, C_{CP}, calculated as:

$$C_{CP} = \frac{NT_g}{T_{spf}} \tag{12}$$

where N is the total number of symbols in the superframe and it is assumed that T_g does not change during operation once a CP ratio is selected. From the results in Table VII we can see that the overhead induced could be as high as 19.2% when the CP of 1/4 is used.

TABLE VII. CP OVERHEAD AND ΔLMAX IN 802.16M SYSTEMS

BW (MHz)	CP ratio	CP superframe overhead (%)	ΔL_{max} (km)
5/10/20	1/8	10.74	0.788
	1/16	5.714	0.394
	1/4	19.2	1.576
7	1/8	10.56	1.103
	1/16	5.6	0.551
	1/4	19.2	2.206
8.75	1/8	10.75	0.882
	1/16	5.63	0.441
	1/4	18.94	1.765

VI. CONCLUSION

IEEE 802.16m standard provides mechanisms which make feasible application of RoF techniques, although they might be affected by the delay caused by the fiber distribution network. Thus, limitations might be imposed on the architecture of the optical distribution network in a RoF 802.16m scenario. In order to preserve correct protocol operation and achieve the best performance, a combination of adapted guard times, ranging channel structure and CP is necessary. For 10 MHz bandwidth for example, our analysis shows that if the fiber lengths and the differences between them do not exceed 5.8 km and 0.8 km respectively, correct protocol operation with minimum efficiency loss could be achieved by increasing the guard time by one OFDMA symbol, while using a CP of 1/8.

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