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FUZZY WEIGHT CONTROLLER BASED CELL-SITE DIVERSITY FOR RAIN FADING MITIGATION IN LMDS NETWORKS IN THE TROPICS

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Abstract—Local multipoint distribution service (LMDS) is a broadband wireless access technology that operates at microwave frequencies above 25 GHz. However, severe attenuation due to excessive rain in tropical regions presents a major challenge for achieving reliable communication over such frequencies. To overcome this problem, cell-site diversity (CSD) can be deployed in cellular-type LMDS networks. In this paper, we address the problem of reliable communication for LMDS networks in heavy rain regions by proposing a fuzzy weight controller based cell-site diversity (FWC-CSD) scheme. Rain cells are randomly simulated in an LMDS network to analyze the system performance using the proposed FWC-CSD scheme. Simulation results show that the proposed scheme yields improved performance in terms of average outage probability and throughput while maintaining the overall quality of service.

1. INTRODUCTION

During the past decade, the emerging demand for high-speed broadband wireless access (BWA) applications has motivated the use of higher frequency spectrum to provide interactive broadband services. In this regard, local multipoint distribution service (LMDS), which is a fixed terrestrial radio technology, has been developed to operate in the 25–43 GHz frequency range [1].

In LMDS systems, wireless links operating at frequency bands above 25 GHz could be disrupted by various channel impairments; among them, rain fading is found to be the most disruptive fading

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mechanism at such frequencies. This problem is particularly serious in the tropics due to frequent rain with heavy downpours. As a result, the reliability and service availability of wireless links are adversely affected.

In the past, rain attenuation mitigation techniques such as adaptive modulation, adaptive power control, fuzzy power control [2] and cell-site diversity (CSD) [3, 4] have been studied. Among these schemes, CSD is found to be the most suitable technique in heavy rain scenarios [5, 6]. In CSD, every customer station (CS) is simultaneously connected to two or more base transceiver stations (BTS). The CS continuously measures the power from each BTS and selects the one with the highest power. The CS may also switch to an alternative BTS (referred to as the diversity BTS in this paper) when it fails to receive signals reliably from its default BTS due to rain fading. To the best of our knowledge, no study on the use of an appropriate antenna plan at the CS site to implement handover for CSD has been published to date.

Existing studies on the conventional CSD scheme only focus on the downstream performance of rain-affected CSs whereby only the service availability of LMDS networks is considered important. In such scenarios, when a CS makes a switch-over to a rain free neighboring BTS, the number of users in the switched-to diversity cell will increase, which in turn reduces the throughput of individual CS. This creates a decision problem for determining the "best time" to perform handover and connect with the "best available diversity BTS" when rain occurs without performing unnecessary handoffs and to re-connect with the default BTS when there is no rain. In fact a similar problem has been reported in [7] where connection admission control (CAC) mechanisms in the context of satellite communication have been studied. Knowledge or prediction of the available capacity within a cell is introduced, which is closely related to the user traffic as well as to the state of the propagation channels for the links from/to the cell considered. In this work we aim to design an effective CSD scheme which can improve the link reliability of LMDS networks.

The key contributions of this paper can be summarized as follows. First, an appropriate antenna plan with switched beamforming capability is proposed to implement the previously proposed CSD method [3] effectively. The proposed switched beamforming based-CSD (SB-CSD) is capable of steering the main beam to a new BTS when a CS fails to receive signals reliably from its default BTS due to rain fading, while suppressing interference from other directions. Second, a fuzzy weight controller is combined with the SB-CSD to handle the switching process adaptively. Since fuzzy logic can deal with multiple variables effectively to reach quick conclusions, the decision problem mentioned earlier could be easily solved using a fuzzy weight controller. In addition to service availability, our investigation is extended to effective network usage wherein improved throughput performance is achieved by individual CSs in the switched-to diversity cell. In the end, we introduce a fuzzy weight control based cell-site diversity (FWC-CSD) solution which can effectively mitigate rain fading while maintaining comparable network accessibility for users of LMDS networks. The salient feature of the proposed method is that diversity signal selection is made provisional through FWC-CSD to maintain good coverage while meeting the throughput requirements.

The rest of this paper is organized as follows. Section 2 briefly describes the cellular architecture of a code division multiple access (CDMA) based LMDS system. Section 3 provides details of the proposed FWC-CSD method. Section 4 conducts a statistical analysis on the downstream signal-to-noise-plus interference ratio (SNIR) and the average outage probability by considering random rain cell movements. Finally, some concluding remarks are given in Section 5.

2. LMDS SYSTEMS

2.1. LMDS System Assumptions and Cell Planning

As depicted in Fig. 1, an LMDS cellular network layout with rectangular cells is adopted. In this work, we consider a CDMA-based cellular LMDS network architecture, which has recently gained considerable interest from the research community [8]. By using the CDMA-based architecture, a simple antenna design is possible as compared with the conventional time division multiple access (TDMA) cell plan [9] which requires multi-band and multi-polarization antenna plan with acceptable cross-polarization rejection. The CDMA network architecture has a frequency reuse factor of one between cells and it reduces the complexity of the uniform circular array (UCA) antenna plan that will be discussed in Section 3.1. In practice, the orthogonal signalling applied in each cell is a two-layer CDMA [8], wherein the transmitted signal is first spread through multiplication by a user-specific Walsh-Hadamard (WH) sequence.

Then, the frequency spread user signal is multiplied by a cell-specific long pseudo noise (PN) sequence. In each cell, the four sectors are separated by using $4N$ orthogonal WH spreading sequences such that each sector can accommodate up to N subscribers. The four disjoint subsets employ each quadrant of a cell and are denoted by "$S1$", "$S2$", "$S3$" and "$S4$", respectively.

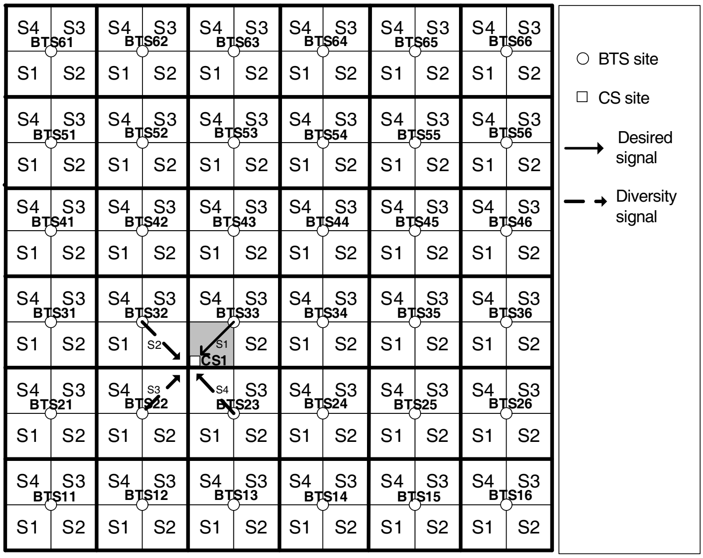

Figure 1. CDMA-based LMDS cell plan.

2.2. Propagation Characteristic and Path Loss Modeling

In previous works [3, 10], an SNIR analysis for rain rates less than 60 mm/h is made. However, the rain rate measurement results obtained in tropical countries show that the rain can exceed 126.8 mm/h for 0.01% of a year [11]. In this work, we study the performance of LMDS operating at 28 GHz in tropical regions by considering rain rates of up to 140 mm/h. Apart from rain attenuation, free space loss and other propagation losses such as atmospheric attenuation are also included in this study.

The ITU-R recommendations are adopted to calculate the specific rain attenuation γ_R [12]

$$\gamma_R = \beta R_{0.01}^{\alpha} \tag{1}$$

where β and α are the model coefficients depending on the frequency, polarization and elevation angle of the radio link. $R_{0.01}$ is the rain rate exceeded for 0.01% of a year. Since the rain is usually not uniformly distributed across a distance, hence the effective path length cannot be considered equal to the actual distance, d, between the transmitting and receiving antennas.

The ITU-R P.530-13 recommendation [13] proposed a model to calculate the effective path length d_{eff} of the link by multiplying the actual path length d by a distance factor r. The distance factor is given by

$$r = \frac{d}{d_o + d} \tag{2}$$

$$d_o = 35e^{-0.015R_{0.01}};\ R_{0.01} \leq 100\,\mathrm{mm/h} \tag{3}$$

$$d_o = 35e^{-0.015\times 100};\ R_{0.01} \geq 100\,\mathrm{mm/h} \tag{4}$$

The total path attenuation, $A_{0.01}$ is given by

$$A_{0.01} = \gamma_R \cdot d_{\mathit{eff}} = \gamma_R \cdot d \cdot r \tag{5}$$

where γ_R is the specific attenuation calculated using (1).

3. FUZZY WEIGHT CONTROL BASED CELL-SITE DIVERSITY

3.1. Combined Switched Beamforming and Cell-site Diversity

CSD has long been recognized as an effective rain fading mitigation scheme especially in heavy rain environments [14]. In tropical regions, high-intensity rain is confined to a small area whereas low-intensity rain normally covers a wider region uniformly. Besides, tropical regions usually suffer from convective rainfalls which are heavy with large rain drops. Such rain is intense but short-lived which lasts for minutes and is localized with random rain cell movements [15, 16]. Thus in heavy rain environments, CSD creates a temporary opportunity for the CS to switch to another BTS in order to achieve better reception in terms of SNIR.

In this work, the scenarios of deploying CSD in an LMDS network are carefully studied before designing an appropriate antenna plan. It should be noted due to line-of-sight propagation, the diversity signals are obtained from neighboring BTSs rather than from multipath propagation. As a result, SB-CSD can be implemented at the CS where the main beam of the antenna is steered towards a new diversity BTS, while suppressing the signals from other BTSs. To accomplish this, the CS shall maintain a list of diversity BTSs that are involved in CSD. For example, the diversity BTSs of CS1 in Fig. 1 consists of BTS22, BTS23 and BTS32. To facilitate the switched beamforming operation, the CS is equipped with an UCA antenna. Since the CS is fixed in LMDS, the beamformer weights for different sets of directions of arrival (DOA) can be predetermined through a short training period and preprogrammed in the CS receiver during setup. For a detailed overview of beamforming, see [17].

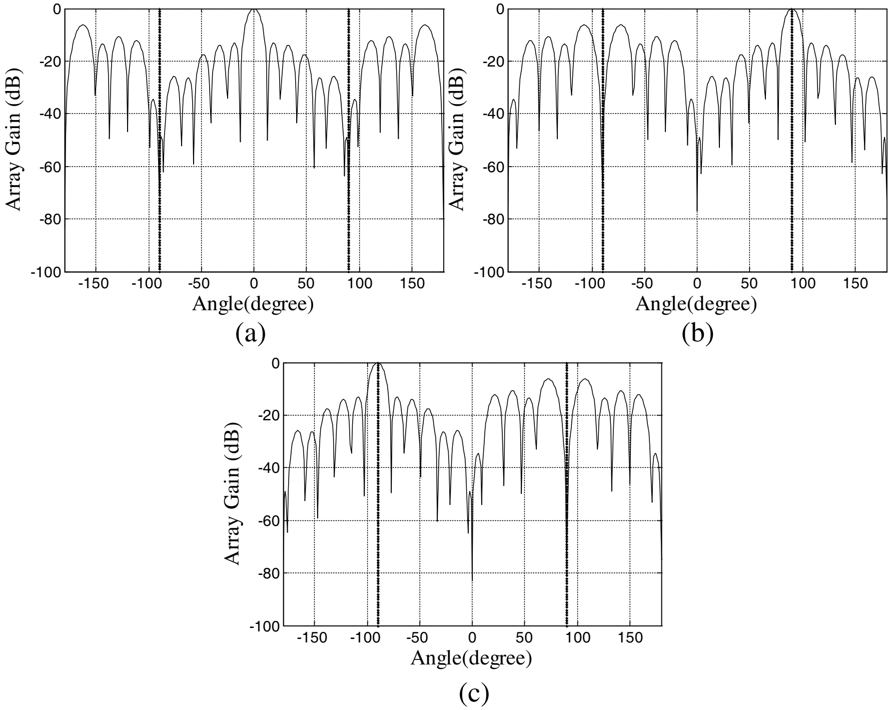

Figure 2. Three sets of beampattern of a 10-element UCA beamformer; (a) A_{r1}, for the default direction (CS1-BTS33), (b) A_{r2}, for the right diversity direction (CS1-BTS23) and (c) A_{r3}, for the left diversity direction (CS1-BTS32).

In the proposed SB-CSD scheme, a 10-element UCA beamformer weights are obtained by the least mean square (LMS) algorithm through training to provide array steering vectors over the DOA range of $[(-180°, 0°)$ and $(0°, 180°)]$ with a $1°$ sampling interval. Fig. 2 depicts the three sets of beam pattern A_{r1}, A_{r2}, and A_{r3} resulting from the use of the beamformer weights W_1, W_2, and W_3, respectively. With this UCA beamformer, the interfering signals can be suppressed by 50 dB.

To this end, an adaptive and effective switching algorithm is required in the SB-CSD scheme for determining the "best time" to perform handover and connect with the "best available diversity BTS" when rain occurs without performing unnecessary handoffs and to reconnect with the default BTS when there is no rain. To facilitate such adaptive switching, a fuzzy logic controller which uses rain rate (in the default path and diversity paths) and channel quality (SNIR) as the input variables, is proposed. In what follows, before outlining the FWC-CSD approach, the basic principles of fuzzy logic are briefly reviewed. For a more comprehensive treatment on this topic, see [18].

3.2. Fuzzy Logic

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with imprecision and information granularity. According to fuzzy set theory, an element can only belong to a set for certain degree. The degree of membership of the element in a fuzzy set X is widely known as the membership value and is represented by a real value in [0, 1]. The fuzzy set X in a universe of discourse U is given by the membership function $X : U \rightarrow [0, 1]$. The fuzzy set X in U is defined as

$$X = \{u, \mu_X(u) \,|u \in U\} \tag{6}$$

where $\mu_X(u)$ is the membership function (MF) of u in X. This MF is associated with the fuzzy set and maps an input value to an appropriate membership value. The mapping process is known as fuzzification. Fuzzy operations are performed on the input and output fuzzy sets in order to develop a fuzzy logic operation. In general, a system may have multilevel inputs and outputs. For instance, consider a fuzzy logic system with two inputs belonging to fuzzy sets $X$and Y. Elementary fuzzy operators such as fuzzy intersection, fuzzy union and fuzzy complement are defined, respectively, as follows

$$\mu_{X\cap Y}(u) = \min\{\mu_X(u), \mu_Y(u)\} \tag{7}$$

$$\mu_{X\cup Y}(u) = \max\{\mu_X(u), \mu_Y(u)\} \tag{8}$$

$$\mu_{\overline{X}}(u) = 1 - \mu_X(u) \tag{9}$$

These fuzzy operators execute the (AND), (OR) and (NOT) operations which are used to formulate the IF-THEN rules. A complete platform that combines the above operators is commonly known as a fuzzy inference system (FIS). In the following section, the FIS structure for the FWC-CSD system is described in detail.

3.3. Fuzzy Inference System of FWC-CSD

Figure 3(a) illustrates the FWC-CSD system which combines a switched beamformer with a fuzzy logic controller. Fig. 3(b) depicts the FIS structure of the proposed FWC-CSD system. The general structure of an FIS consists of three basic parts: the fuzzification interface (fuzzifier) at the input terminal, the inference engine built

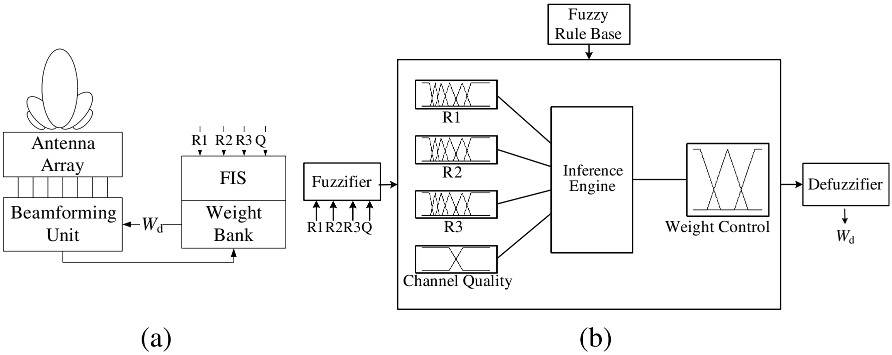

Figure 3. (a) FWC-CSD system. (b) FIS for the FWC-CSD.

on the fuzzy logic control rule base in the core, and the defuzzification unit (defuzzifier) at the output terminal.

The switching carried out by the FWC-CSD scheme is not only based upon the channel quality but the rain rate in the default link and the diversity links. Hence, these parameters form the input MFs for the controller. The rain rate at the mth sampling period can be measured using a rain gauge and a data logger. In practice, a rain gauge is required in each sector of the entire network to measure and update the rain rate information. The rain gauge should be featured with a data logger which can sample data at a 1 second interval and average data over a 1 minute interval. The hourly rainfall rate can be calculated using the software available in the data logger [5, 11]. Alternatively, the system can also adopt the weather forecast data [2]. However, this approach would increase the complexity of the system; therefore it is not considered in this paper.

For the scenario illustrated in Fig. 1, R1 denotes the average rain rate in the default link from CS1 to BS33; R2 and R3 represent the average rain rates in the diversity links, CS1-BTS23 and CS1-BTS32, respectively. A diversity order of three is considered, i.e., one default link and two diversity links. Since LMDS is a two-way point-to-multipoint (PMP) system, where different BTSs can exchange information with each other through upper layer communications [2], the FWC-CSD scheme can be updated with the latest rain rate information. For each of the rain rates R1, R2 and R3, very low (VL), low (LOW), moderate-low (ML), moderate (M), high (HIGH) and very high (VH) are the possible fuzzy variables for fuzzification. In addition, "BAD" and "GOOD" are the fuzzy variables for the channel quality adjusting factor (ΔQ). Thus this FWC-CSD scheme consists of four input membership functions. FWC-CSD is designed to steer the main beam to a preferred direction. Therefore the variable weight control, W_D is used as the output membership function to control the direction of the beam. Fig. 4 and Fig. 5 illustrate the four inputs and one output control variables associated with the proposed FWC-CSD scheme. Note that all the fuzzy MF values lie in the range [0, 1]. The outage probability can be used as a system performance parameter to determine the system capacity and communication link performance. It can also be employed as the basis to build membership functions [2], i.e., the changes in the slope of the outage probability curve are used to construct the membership functions. For instance, MFs for R1, R2 and R3 are designed based on the probabilities or frequencies of rain rates that could minimize the average outage probability. For simplicity, triangular and trapezoidal MFs are used.

The variable ΔQ is dependent on the received SNIR. This variable

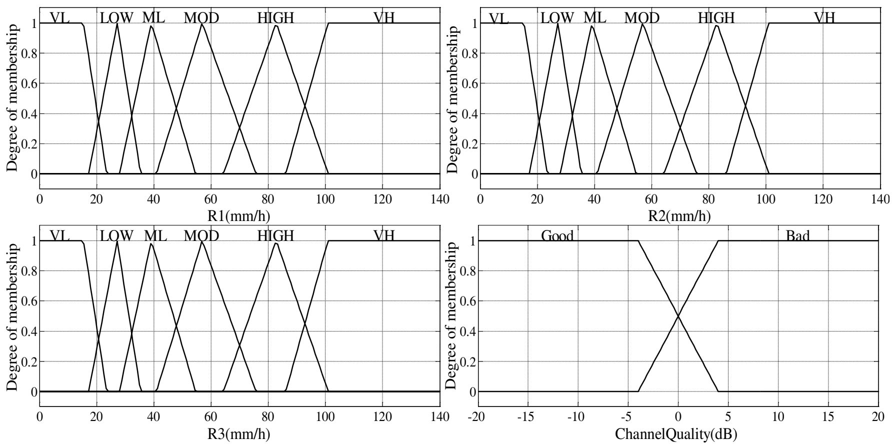

Figure 4. Input membership functions of FWC-CSD.

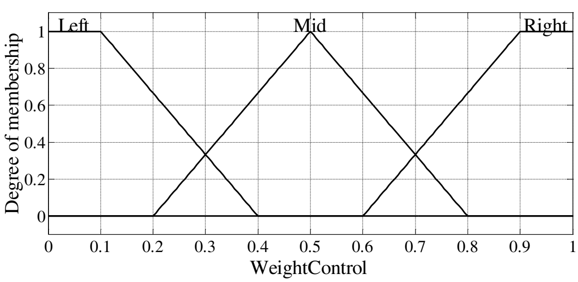

Figure 5. Output membership function of FWC-CSD.

is included as a MF to improve the decision control of the FWC-CSD scheme. The variable W_D is a linguistic control output variable of the FWC-CSD scheme. At the mth sampling period, W_D is obtained from defuzzification with a centroid method [18] and is given by

$$W_D\,(m) = F\,\{R_1(m), R_2(m), R_3(m), \Delta Q(m)\} \tag{10}$$

and

$$\Delta Q(m) = \gamma_{th} - SNIR(m-1) \tag{11}$$

where F denotes the fuzzy inference function and γ_{th} is the SNIR threshold. Note that γ_{th} and SNIR are all in dB. The variable W_D is used as the decision parameter to map the desired weight at the receiver.

$$W_D = \begin{cases} W_1, \text{Mid} \\ W_2, \text{Right} \\ W_3, \text{Left} \end{cases} \tag{12}$$

As described in Section 3.1, the desired weights (W_1, W_2 and W_3) for each CS are pre-computed. The fuzzy inference engine formulates a set of IF-THEN rules and performs fuzzy decision making based on two different scenarios: diversity scenario and default scenario. The diversity rules are applied to the diversity scenario when it is necessary to switch the CS to a diversity BTS to mitigate heavy rain, i.e., the following rule:

> "**IF** *R1 is HIGH and R2 is VL and R3 is not VL and* ΔQ *is BAD* **THEN** *the* W_D *is Right"*
> allows the CS to switch to BTS23 in the event that a heavy downpour blocks the path CS-BTS33.

The default rules are applied to relocate the CS back to its default BTS when the latter is available, i.e., the following rule:

> "**IF** *R1 is VL* **THEN** *the* W_D *is Middle"*
> instructs the CS to switch back to the default BTS when the CS-BTS33 path is clear from rain. In order to reduce the complexity of the FWC-CSD system, only rules that are useful for the above scenarios are implemented.

4. NUMERICAL ANALYSIS

In this section, we conduct numerical analyses in terms of average outage probability and throughput analysis to compare the performance of relevant CSD schemes. Since the customers located at the edge of a cell suffer from the worst case SNIR [1, 19], the investigation is only focused on such scenarios. A CDMA-based downstream SNIR model from [20] is adopted and by including the normalized gain for the desired signal and interference signals, the SNIR is given by,

$$SNIR = \frac{10^{\left(\frac{A_D - L_C}{10}\right)}}{10^{\left(\frac{P_n-(P_t+G_t+G_r)}{10}\right)} + N\sum_{k=1}^{M} 10^{\left(\frac{A_{I_k}-L_{I_k}}{10}\right)}} \times \frac{\zeta}{R} \tag{13}$$

where the average normalized gains of the CS antenna at the desired angle and interference angle are represented by A_D and A_I respectively. L_C and L_I indicate the total losses on the desired path and the M interfering paths, respectively. The chip rate and the nominal bit rate are represented by ζ and R, respectively; the system spreading factor ζ/Rindicates the system's ability to eliminate interference. In this work, $\zeta/R = 4N$ is taken according to [20].

The outage probability is defined as the probability of having an SNIR corresponding to the ith rain rate sample, ($SNIR_i$) less than a target γ_{th} using a specific modulation scheme at a given bit error rate (BER). In this analysis, the threshold is set to 12.3 dB, which corresponds to the reference SNIR required to achieve a BER of 10^{-6} using QPSK modulation [2]. In the simulation, the range of rain rate considered on the default path is between 0 mm/h to 140 mm/h with a stepwise increment of 10 mm/h. For each fixed rain rate on the default path, random rain rates (0–140 mm/h) on the diversity paths are generated uniformly N_t times, where N_t denotes the number of simulation trials. For instance, if the rain rate on the default path is 0 mm/h, random rain rates are generated N_t times only on the diversity paths to obtain N_t outage probability values. The outage probability of a link for the ith iteration, P^i_{out} is defined as,

$$P^i_{out} = [SNIR_i < \gamma_{th}]. \tag{14}$$

The average probability, P_{out} at each step is given by

$$P_{out} = \frac{1}{N_t}\sum_{i=1}^{N_t} P^i_{out}. \tag{15}$$

4.1. Service Availability Improvement with FWC-CSD

The following schemes are compared through simulations:

1. Conventional: This receiver employs neither the SB-CSD plan nor the FWC-CSD scheme. The conventional antenna model [21] is considered for this receiver.

2. SB-CSD: This receiver is equipped with the switched beamforming based CSD scheme as described in Section 3.1.
3. FWC-CSD: This scheme denotes the receiver incorporating the proposed FWC-CSD scheme as described in Section 3.2.

The analysis carried out in this section only focuses on the users affected by rain. Since both the FWC-CSD and SB-CSD schemes use the SNIR as the decision parameter to perform switching, they provide comparable service availability for the rain-affected users. In other words, the average outage probability performance of both the FWC-CSD scheme and the conventional SNIR-based SB-CSD scheme is similar. An analysis on the performance of the FWC-CSD approach to the switched-to diversity BTS will be demonstrated in Section 4.2.

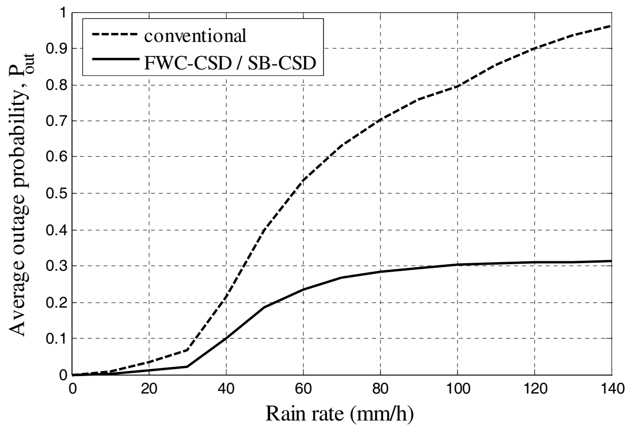

Figure 6. Average outage probability performance up to a maximum rain rate of 140 mm/h.

The average outage probability performance of LMDS systems using different schemes is shown in Fig. 6. In the simulations, the maximum rain rate considered is 140 mm/h. As expected, it is observed that the conventional system performs poorly at higher rain rates. In particular, over the rain rates of 60 mm/h to 140 mm/h, a performance improvement of approximately 30% is achieved by the FWC-CSD-based system over the conventional system.

4.2. Throughput Improvement with FWC-CSD

In this section we attempt to elucidate the mechanism of FWC-CSD which can be useful in providing diversity to the rain-affected CS while maintaining the overall network throughput. With reference to

Fig. 1, in the event that rain occurs in path CS1-BTS33 (BTS33 is the default BTS), the FWC-CSD scheme can switch CS1 to BTS23 (BTS23 becomes the diversity BTS). The time series record in [5] for some rain rates measured in a tropical environment is adopted to simulate the rain event in sector S1-BTS33. Meanwhile, the path CS1-BTS23 is assumed to be free from heavy rain fall. After the switch-over, however, the network traffic in sector S4-BTS23 is increased.

Simulations were performed with the assumption that each sector is fully loaded with 64 users offered with a global throughput (R_g) of 622 Mbps and the rain-affected CSs from sector S1-BTS33 switch to BTS23. Consequently, as the number of CSs accommodated is substantially higher than N, the overall performance in sector S4-BTS23 starts degrading from the optimum level. The performance in sector S4-BTS23 is studied in terms of average throughput.

Figure 7(a) shows the rain time series simulated in sector S1-BTS33. Fig. 7(b) indicates that when heavy rain occurs (e.g., over the 15th–75th min interval), the received SNIR of a conventional receiver falls below the required SNIR threshold of 12.3 dB. In contrast, since both the FWC-CSD and SB-CSD schemes can provide the rain-affected

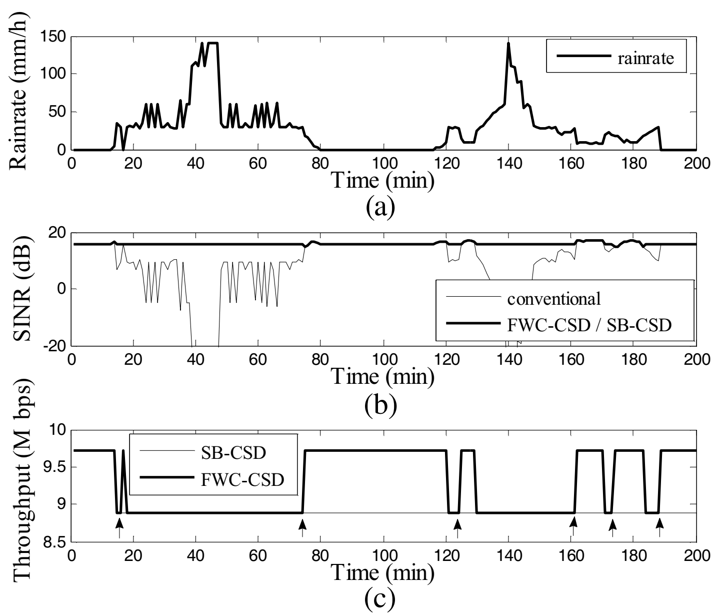

Figure 7. (a) Time series of rain rate in sector S1-BTS33; (b) SNIR of rain-affected CSs in sector S1-BTS33; (c) Average throughput of CSs in sector S4-BTS23.

CSs with a diversity link from BTS23, better reception in terms of SNIR is obtained. Meanwhile, Fig. 7(c) depicts the average throughput $R_a = R_g/(N + N_d)$ in sector S4-BTS23, where N_d denotes the number of rain-affected users from sector S1-BTS33, which equals to 6 in this simulation. In order to accommodate these CSs, a throughput reduction is to be compromised by all CSs in this sector.

In Fig. 7(c), it is observed that during 15th–75th min interval, the average throughput of the FWC-CSD and SB-CSD schemes drops from 9.8 Mbps to 8.88 Mbps. After the 75th min, despite the fact that sector S1-BTS33 is almost clear from rain block, the rain-affected CSs using the SB-CSD scheme are still communicating with BTS23, whereas the FWC-CSD scheme is able to monitor the channel variation in the default path and manages to relocate these CSs back to the default BTS (BTS33). The arrows in Fig. 7(c) indicate the time when the FWC-CSD scheme attempts to relocate the rain-affected CSs back to BTS33.

Figure 8 shows the performance comparison of the FWC-CSD and CSD schemes in terms of total received data in sector S4-BTS23 under different values of N_d. Overall, it is found that the total received data can be increased by using the FWC-CSD scheme. This improved performance in the FWC-CSD scheme is attributed to its adaptive feature in relocating rain-affected users to diversity links for better signal reception.

Furthermore, the FWC-CSD scheme also yields an improvement over the SB-CSD scheme as the number of rain-affected CSs switched

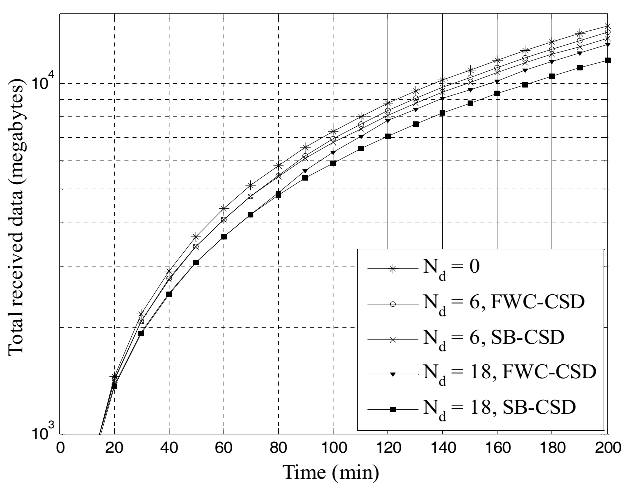

Figure 8. Average achievable data rate in sector S4-BTS23.

to the diversity BTS increases. For instance, when $N_d = 18$, it can be seen that the FWC-CSD scheme can achieve 10^4 Mbytes of total data approximately 20 minutes earlier as compared with the SB-CSD scheme. In urban areas, since the user density in LMDS networks is usually high, the FWC-CSD scheme can be particularly attractive in such scenarios.

5. CONCLUSION

In this paper, we investigated the use of FWC combined with CSD to improve the reliability of LMDS networks against rain fading. The FWC incorporates a switched beamforming-based CSD, which provides an adaptive decision making mechanism to relocate rain-affected CSs according to the rain scenarios. Simulation results show that deploying the proposed FWC-CSD scheme can improve the average outage probability performance while maintaining comparable service delivery for all users when heavy rain occurs in LMDS networks.

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