FREQUENCY SCALING IN MILLIMETRE-WAVE RAIN ATTENUATION ESTIMATION FOR SATELLITE LINK IN TROPICAL REGIONS

BY

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ABSTRACT

The congestion at the lower frequency bands is pushing the demands for the usage and operation in the higher bands. The bands above 10 GHz are now required to satisfy the tremendously increasing needs in satellite communication (SatCom) systems. The biggest problem in deploying frequencies above 10 GHz in tropical-equatorial regions is that such areas will experience acute degradation of signal quality due to heavy rainfall throughout the year. A reliable estimation of rain attenuation is required. Dependable fade margins are required in mitigating the harsh signal losses. It is found that data validation for rain attenuation estimation using the frequency scaling technique is not available in any previous studies conducted in tropical regions. It has been suggested that instead of using the conventional method of predicting rain attenuation using the point rainfall rate information, an applicable non-meteorological technique should also be established. A frequency scaling technique can be the alternatives mean to predict rain attenuation when rainfall data is not available. The objectives of the research entail rain-induced attenuation studies for SatCom in tropical regions. They comprise identifying the best fade margin for rain attenuation at various links, formulating a new frequency scaling model with improved accuracy, and validating the proposed model. The methodologies involved in the study encompass the processing of the beacon signals into first-order statistics of rain attenuation. This, later, leads to the generation of monthly and annual rain attenuation Cumulative Distribution Functions (CDFs). The worst month analysis for rain intensity and rain attenuation was also carried out. The signal loss is expected to be appalling in the worst month because of the high occurrence of rain events. The required fade margin was determined from an exceedance at a specific point from the annual CDF. In brief, the frequency scaling model was derived based on the correlation between the attenuation ratio of a higher and lower frequency against the attenuation at a lower frequency. The newly developed formulation was utilized to generate new CDFs of attenuation at different frequencies. The proposed model offers a lower RMSE value and percentage error of 2.8 and 11.3% respectively. In contrast, the generic method suggested by the ITU-R only managed to perform prediction with RMSE value and percentage errors of 28.3 and 28% accordingly. The new model was validated using data set from alternative years and alternate locations. In conclusion, the results from the research demonstrate a model that can be used in the tropical-equatorial region in a way denoting the achievement of fulfilling the stated objectives. The satellite signal performance can be improved by applying developed mitigation techniques with an economically viable cost where dependable fade margins can be attained. The newly developed frequency scaling technique can offer the right margin to achieve the required quality of service (QoS) for future SatCom in supporting near-future 5G communication. Consistent connectivity for high-speed broadband communication demand in delivering digital and internet applications during heavy precipitation can be attained.

خلاصة البحث

يؤدي الازدحام في نطاقات التردد المنخفضة إلى زيادة الطلب على استخدام وتشغيل نطاقات التردد الأعلى. لذلك، فإنّ النطاقات فوق 10 جيجاهرتز مطلوبة الآن لتلبية الاحتياجات المتزايدة بشكل كبير في أنظمة اتصالات الأقمار الاصطناعية (SatCom). ولكنّ أكبر مشكلة في نشر الترددات فوق 10 جيجاهرتز في المناطق الاستوائية المدارية هي أن هذه المناطق ستشهد تدهوراً حاداً في جودة الإشارة بسبب هطل الأمطار الغزيرة على مدار العام. فمن المطلوب تقدير موثوق للتوهين الناجم عن المطر. وكذلك، هناك حاجة لهوامش تلاشي موثوقة للتخفيف من الخسائر الحادّة في الإشارة. لقد وجد أن التحقق من صحة البيانات لتقدير التوهين الناجم عن المطر باستخدام تقنية تعديل التردد (Frequency Scaling) لم يرد في أي دراسات سابقة أجريت في المناطق المدارية. لذا يقترح هذا البحث أنه بدلاً من استخدام الطريقة التقليدية للتنبؤ بالتوهين الناجم عن المطر باستخدام معلومات معدل هطل المطر النقطي، ينبغي أيضاً إنشاء تقنية قابلة للتطبيق غير متعلقة بالأرصاد الجوية. ويمكن أن تكون تقنية تعديل التردد هي الوسيلة البديلة للتنبؤ بالتوهين الناجم عن المطر عندما لا تتوفر بيانات هطل الأمطار. تتضمن أهداف البحث دراسات التوهين الناجم عن المطر لاتصالات الأقمار الاصطناعية (SatCom) في المناطق المدارية. وتشمل تحديد أفضل هامش تلاشي للتوهين الناجم عن المطر في وصلات مختلفة، وصياغة نموذج جديد لتعديل التردد بدقة محسنة، والتحقق من صحة النموذج المقترح. كما تشمل المنهجيات المتضمنة في الدراسة معالجة الإشارات المرسلة للحصول على إحصائيات أولية للتوهين الناجم عن المطر. ويؤدي هذا لاحقاً إلى توليد دوالّ توزيع تراكمي (CDFs) للتوهين الناجم عن المطر شهرية وسنوية. كما تم إجراء تحليل الشهر الأسوأ لكثافة المطر والتوهين الناجم عن المطر. حيث من المتوقع أن تكون خسارة الإشارة مروعة في أسوأ شهر بسبب ارتفاع معدل هطل المطر. وقد تم تحديد هامش التلاشي المطلوب من خلال تجاوز الحد الأقصى عند نقطة معينة من (CDF) السنوي. باختصار، تم اشتقاق نموذج تعديل التردد بناءً على الارتباط بين نسبة التوهين لتردد أعلى وتردد أدنى مقابل التوهين عند تردد أدنى. كما تم استخدام الصيغة المطورة حديثاً لتوليد (CDFs) جديدة للتوهين عند ترددات مختلفة. يقدم النموذج المقترح قيمة (RMSE) ونسبة خطأ بمقدار 2.8 و 11.3٪ على التوالي. وعلى النقيض من ذلك، فإن الطريقة العامة التي اقترحها قطاع الاتصالات الراديوية (ITU-R) لم تتمكن إلا من التنبؤ بقيمة (RMSE) ونسبة خطأ بمقدار 28.3 و 28٪ على التوالي. تم التحقق من صحة النموذج الجديد باستخدام مجموعة بيانات من سنوات مختلفة ومواقع مختلفة. وفي الختام، تظهر نتائج البحث نموذجاً يمكن استخدامه في المنطقة الاستوائية المدارية بطريقة

تدل على تحقيق الأهداف المذكورة. يمكن تحسين أداء إشارة القمر الاصطناعي من خلال تطبيق تقنيات تخفيف مطورة بتكلفة مجدية اقتصادياً، حيث يمكن تحقيق هوامش تلاشي موثوقة. ويمكن أن توفر تقنية تعديل التردد المطورة حديثاً الهامش الصحيح لتحقيق جودة الخدمة (QoS) المطلوبة لاتصالات الأقمار الاصطناعية (SatCom) المستقبلية في دعم اتصالات الجيل الخامس (5G) في المستقبل القريب. كما يمكن تحقيق اتصال ثابت لتلبية حاجة اتصالات النطاق العريض عالي السرعة في تقديم التطبيقات الرقمية وتطبيقات الإنترنت أثناء هطل الأمطار الغزيرة.

APPROVAL PAGE

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DECLARATION

I hereby declare that this dissertation is the result of my investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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Signature .... Date 11th April 2023

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This thesis is dedicated to my beloved father and my late mother for laying the foundation of what I turned out to be in life.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The Covid-19 global pandemic has caused serious problems for the world's leading satellite industries. They faced several challenges in delivering reliable link availability of satellite-Earth signals. Since the start of the pandemic, broadband connectivity provided by satellite operators had drastically increased from 15% to 70% in network usage. Satellites can instantly connect isolated communities and offer connectivity to unreachable and remote areas. However, the main challenge experienced by satellite industries is providing consistent internet connection in places that experience frequent heavy precipitation where severe impairment of satellite signal reception occurs. Precipitation like rain prominently degrades the quality of satellite signals. When signals travel from satellites to the Earth's receivers, they pass over unpredictable rain along their propagation paths. The signal power may weaken before reaching its destination, especially when longer slant paths and lower elevation angles are involved (Igwe et al., 2019; Nazrul et al., 2013). These factors affect link availability, leading to negatively impacting consumer satisfaction which further damages and causes a tumble in the reputation of satellite providers.

The International Telecommunication Union´s (ITU) Radio Regulations (RR) defined satellite links as radio links transmitting between Earth stations to satellite receivers and vice versa. An "uplink" refers to an Earth-to-satellite propagation, and a "downlink" implies transmission from the satellite to a receiving Earth station. Radio frequencies that have wavelengths (λ) ranging between 1 mm to 10 mm in satellite-Earth links are referred to as millimetre-wave frequencies. Communication satellites facilitate human connection regardless of location (Badron et al., 2015). Satellite communication (SatCom) is then considered the best option for addressing user demands for areas not economically reachable by terrestrial links, such as for developing countries with vast lands or in the middle of the ocean. Numerous requirements in the telecommunication and broadcasting industries have prompted an increase in demand for high-speed broadband communication, especially for multimedia services. These have subsequently led to the growing demands for greater bandwidth (Yussuff et al., 2019). Although the rollout of fibre in South Africa significantly enhanced the speed of home broadband in the year 2014, satellite infrastructures continue to fulfil a crucial role in providing communication access to rural, remote and inland areas throughout the continent and across the globe as well. The fast growth in telecommunications, increasing bandwidth demands, congestion in lower frequency bands, and miniaturisation of communication equipment have forced designers to employ higher frequency bands such as the Ku (12 to 18 GHz), Ka (26.5 to 40 GHz) and V (40 to 75 GHz) (Kamruzzaman & Islam, 2014). Unfortunately, higher operating frequency bands are very susceptible and vulnerable to tropospheric conditions that impair and reduce signal quality (Sujimol et al., 2015).

The proposed satellite television broadcast for home reception is called Direct Broadcast Satellite (DBS) or Direct-to-Home (DTH). It enables the easy access to live television channels from other countries. Various multimedia applications are offered by satellite communication which all require extremely high data rate transmissions, including videoconferencing, broadcasts, data broadcasts that include High Definition (HD) television broadcasts, bandwidth on demand, intranet works and telemedicine. Such applications lead to spectrum congestion in lower frequency bands. Shifting to higher frequency bands is one option for achieving better services in satellite communication applications since these bands support high data-rate broadcasts and internet applications. SatCom systems are now moving towards the use of Ka-bands (20/30 GHz). In future, the shift to higher frequency bands, such as the Q/V (40/50 GHz), will undoubtedly occur to accommodate larger bandwidth requirements. High radio frequency offers several advantages such as larger spectrum availability, smaller equipment size requirements and less interference for SatCom (Samat & Singh, 2020).

High Throughput Satellites (HTS) are communication satellites with higher throughput than traditional Fixed Satellite Services (FSS) which give advantages in frequency reuse and multiple spot beams. High throughput is important because of its high-speed information delivery (bits/sec). It can be influenced by frequency reuse and channel efficiency. The first commercial HTS in Asia is the IPSTAR (Thaicom-4) operating in the Ku-band and is now developing to operate in the Ka-band (ITU-R P.618-13, 2017). The main purpose of these satellites is fast internet connectivity. The commercial HTS, IPSTAR, was launched by Thaicom in 2005. This satellite was designed for FSS, which is a two-way communication over an Internet Protocol (IP) platform with a maximum capacity throughput of 45 Gbps, a user download speed of up to 5 Mbps and an upload speed of 4 Mbps.

Today, the IPSTAR is licensed to operate in 14 countries in the Asia Pacific areas, which directly allows service providers and operators to deliver real-time broadband internet access via satellite. In May 2011, Thaicom began selling some parts of its satellite capacity to Malaysia. Malaysia’s satellite operator, MEASAT, signed a contract for a specific capacity on the IPSTAR. MEASAT Satellite Systems Sdn. Bhd. purchased access to seven IPSTAR spot beams under a decade contract for delivering a total of 3.3 Gbps, representing 7% of the satellite’s total capacity. The bandwidth was known and marketed in Malaysia as MEASAT-5 (Christensen, 2012).

The idea of deploying a new satellite system in the Ka-band frequency started to evolve and gain attention in countries with tropical environments. The areas between the Earth's latitudes of 23°27′ North and 23°27′ South are identified as tropical regions, as shown in Figure 1.1. The propagation impairments are quite critical in locations with tropical weather. This is due to the occurrence of frequent heavy rain which severely affects high-frequency radio wave signals. The rain can cause severe signal fading as well as interference (Yeo et al., 2009a). The dominant factor for signal impairment of satellite links at higher frequencies is rain, and this depends on the rain rate, the raindrop size and raindrop density (Kamruzzaman & Islam, 2014; Islam et al., 2018). Raindrops absorb and scatter radio waves with shorter wavelengths, hence resulting in signal attenuation as well as reducing system availability and reliability (Mom et al., 2021). The attenuation due to rain on any path depends on several parameters, such as the specific attenuation in dB/km, frequency, polarization, temperature, path length and latitude. As it is known rain attenuation causes a reduction of the received signal level, therefore, upon designing dependable Ka-band satellite communication systems, rain attenuation must be considered as an important propagation element to ensure signal quality. The conventional quality of service (QoS) criterion in Malaysia for broadcasts is 99.99% availability (MCMC, 2022). The QoS requirement recommended by the ITU-R Telecommunication Standardisation is 99.9% link availability for communication services (ITU-T G.1028, 2016).

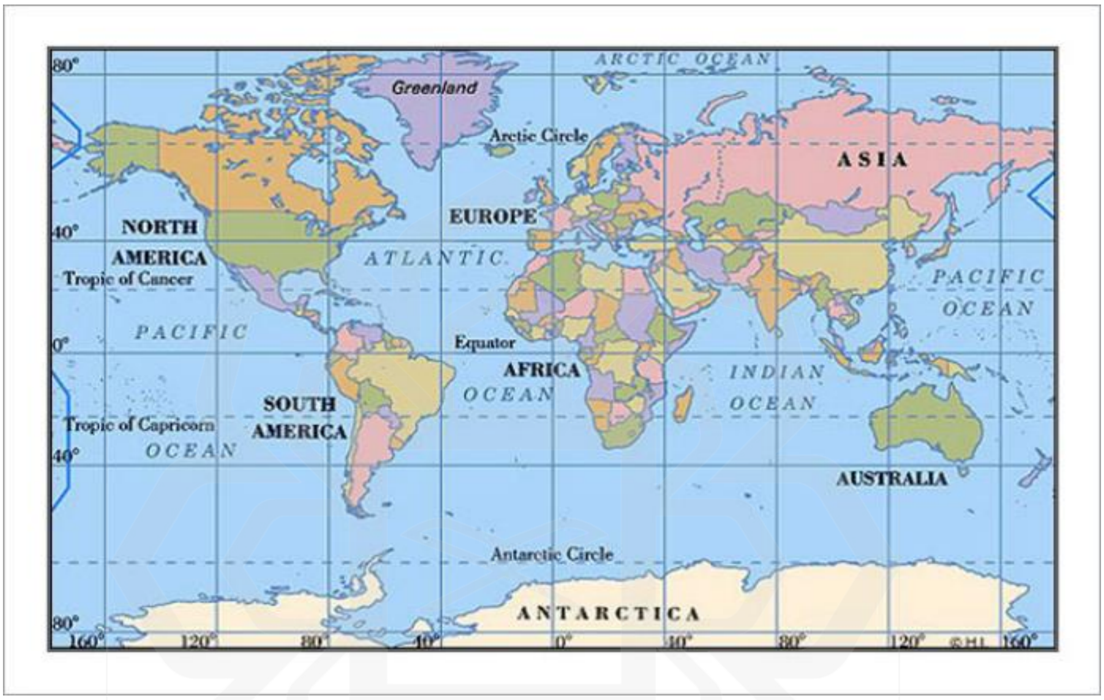

Figure 1.1 Map of Tropical Regions (IEEI, 2014)

Rain attenuation is typically assumed as a product of specific attenuation (dB/km) and the effective propagation path length (km). The effective path length is the product of the path reduction factor and the physical path length of a microwave link (Islam et al., 2012). Rain is the most destructive source of signal propagation on these bands. The consequence of rain attenuation on band signal quality, especially in tropical countries such as Malaysia, requires comprehensive research. The appropriate fade margins must be identified to ensure successful implementation in all provinces throughout Malaysia.

Several methods can be used for identifying and estimating rain attenuation. The frequency scaling technique is one suggested approach (Ulaganathen et al., 2013). Frequency scaling of attenuation is the prediction of rain attenuation at the desired frequency derived from attenuation values at another frequency (Laster & Stutzman, 1995; Ramana, 2015; Ulaganathen et al., 2013). The method can be used to obtain an estimation of the attenuation statistics at the desired frequency from attenuation values measured at a lower frequency. This is very much applicable where and when reliable long-term rain attenuation statistics are available. Numerous scaling models have been developed either from theory, from empirical data of various propagation experiments or from both (Islam et al., 1999).

Generally, statistical models (such as ITU-R) are suitable for establishing fade margins to mitigate the impairment of transmitted signals. However, it has been highlighted by various research that the proposed margin cannot cater to large attenuations and acute impairments in tropical regions (Ismail et al., 2013; Sujimol et al., 2015; Yaccop et al., 2016). The design and deployment of satellite systems in tropical regions for higher frequencies require an accurate and precise prediction of impairment statistics. The statistics must have the smallest error margin to employ several adaptive techniques at the receiver system. This applies to Malaysia, a country with a tropical climate with persistent heavy rainfall every year. The research outcomes will help in solving the relevant problems and setting an appropriate link budget when designing new satellite networks. Appropriate allocation of higher power transmission can be deployed to overcome rain fade endured by higher frequency satellite-Earth links.

1.2 PROBLEM STATEMENT

The terrestrial network has a serious limitation in terms of offering mass coverage for rural areas and isolated locations. This can be complemented by satellite-Earth