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Spectrum Congestion, Connectivity Gaps, and RF Monitoring in Uganda (2018–Present)

Spectrum Usage Growth and Congestion in Uganda

Uganda's commercial wireless networks have experienced rapid growth in traffic and infrastructure in recent years, leading to concerns of spectrum congestion. **Mobile data usage has exploded:** Uganda's mobile internet traffic roughly doubled from **217 million GB in 2021** to **421.5 million GB in 2022**, according to Uganda Communications Commission (UCC) reports [1] (published 2023). This surge reflects booming 4G data consumption and smartphone uptake. To support demand, **network infrastructure has expanded** – as of March 2022 there were **over 30.6 million mobile subscriptions** and **4,300+ base station sites** active across Uganda [2], indicating widespread deployment of 2G/3G/4G Base Transceiver Stations (BTS). Nevertheless, operators face **spectrum licensing constraints**: until recently, only limited frequency bands were allocated for 4G/5G. UCC's multi-band auction in 2022–2023 released new spectrum (e.g. 700 MHz, 800 MHz "digital dividend" bands, 2.3–3.5 GHz, etc.) to MTN and Airtel [3], aiming to alleviate the crunch and enable 5G rollouts. Even so, urban areas like Kampala often see heavy spectrum utilization, with numerous carriers and technologies overlapping. Congested bands increase interference and raise the noise floor.

Impact on modulation recognition: Spectrum congestion means wireless receivers encounter more overlapping signals and radio-frequency noise. Research in 2025 notes that the rise of end-users and wireless services has "**intensified radio spectrum congestion**" [4]. This directly challenges **Automatic Modulation Classification (AMC)** in cognitive radio systems – it is harder to reliably identify signal modulation types amid dense interference. Cognitive radios rely on modulation sensing to dynamically access free channels; under high congestion, misclassification can occur if signals collide. Thus, Uganda's congestion context underscores the need for *noise-robust* AMC techniques (such as deep learning classifiers with DAE denoising) to maintain accuracy. In fact, robust AMC is considered critical in advanced wireless design – it is "one of the basic building blocks" of both cognitive radio receivers and electronic warfare receivers [5]. Improving AMC resilience to noise/interference helps **cognitive spectrum management**: for example, an SDR base station with AMC+DAE could better distinguish users' modulation schemes on a crowded tower, or a dynamic spectrum access system could detect an empty channel despite adjacent-band interference. In summary, Uganda's fast-growing spectrum usage (with doubling data traffic and expanding BTS deployments) risks congestion that complicates signal classification, motivating more sophisticated SDR/AMC solutions.

Sources: UCC market report (2023) [1]; UCC/KIU study (2023) [2]; GSMA/TeleGeography news (2022) [3]; Yu *et al.*, *Sci. China Inf. Sci.* (2025) [4]; Cutno (Master's thesis, 2016) [5].

Rural Connectivity Gaps in Uganda

Despite overall progress, **rural Uganda faces significant connectivity gaps**. A large portion of the population still lacks **reliable broadband or mobile coverage** outside urban centers:

- **Coverage deficits:** By end of 2021, **3G mobile coverage reached 93% of the population**, up from 63% in 2016, while 4G coverage reached ~79% [6]. This means roughly **7% of Ugandans (mostly in remote rural areas) had no access to even 3G service** as of 2021. By 2025, coverage improved further – the GSMA reports Uganda achieved **over 96% population coverage with 3G/4G** infrastructure [7]. However, coverage is not universal: many sparsely populated villages still fall outside base station range (or only have a weak 2G signal). A 2024 investment report noted that "only **65% of Uganda** [by area] has mobile network coverage" currently, and set a goal of 95% coverage in coming years [8]. These gaps are concentrated in rural districts, especially in mountainous or hard-to-reach regions (e.g. parts of Karamoja, Northern Uganda). UCC's own assessments identified **117 sub-counties with less than 30% 3G coverage** as of 2022 [9] – a clear indication of underserved rural pockets.

- **Offline population:** Due to these coverage gaps (and other barriers like cost), a large share of Ugandans remain offline. In 2024, an estimated **30 million people in Uganda (≈62% of the population) had no access to mobile internet** [10]. Even by 2025, **only ~30% of Ugandans were active internet users** while 70% stayed offline [11] [12]. The majority of the offline population resides in rural areas. This "usage gap" persists despite infrastructure presence, pointing to issues like device affordability, digital literacy, and network quality. Still, pure lack of coverage is a foundational problem for many villages – without a signal, there is no opportunity to get online.

- **Government and UCC initiatives:** To close the rural connectivity gap, Uganda has undertaken several programs. The **National Backbone Infrastructure (NBI)** project (operational since late 2010s) extended over 2,400 km of fiber optic backbone across the country, linking up-country towns and border regions to high-speed backhaul [13]. This backbone enables telecom operators to reach rural areas with capacity (and connect public institutions – schools, hospitals – under e-government plans). UCC also manages a **Rural Communications Development Fund (RCDF)**, now branded UCUSAF (Universal Service Access Fund), which subsidizes telecom expansion in unprofitable rural markets. Under the **UCUSAF Access Infrastructure Program (2022–2027)**, UCC is co-funding **200 new rural cell sites** in those 117 under-covered sub-counties [9]. The first phase (63 tower sites) launched in 2023 in partnership with a tower company, targeting villages with no signal [14]. Additionally, in March 2024 a consortium of European development banks lent $40 million to deploy **506 new mobile towers in rural Uganda** [15] [16] – a project expected to boost 4G/5G coverage in remote communities and help reach Uganda's 95% population coverage goal. These initiatives, along with programs to provide solar power for rural towers and community Wi-Fi hubs, illustrate the concerted effort to bridge the rural digital divide.

- **Technical conditions (low SNR & multipath):** Even where rural networks exist, they often suffer **poor signal quality**. Base stations in rural Uganda typically serve large cell radii (many kilometers) with few sites, so users at the fringes experience **low signal-to-noise ratios (SNR)** and intermittent connectivity. For example, a farmer 10–15 km from the nearest tower might only get a 1-bar EDGE/3G signal, especially during bad weather. Terrain and vegetation further attenuate signals – Uganda's rural landscape includes hills, forests, and scattered homesteads, which can introduce **multipath**

fading and shadowing. While open rural areas have less dense multipath than cities, **hilly or wooded rural areas still create signal reflections and delays** that distort the radio channel. The combination of low SNR and multipath interference leads to high error rates and dropped connections for rural users. These challenging conditions are precisely where *noise-robust AMC* can aid SDR deployments: an SDR system using an **Autoencoder-based denoiser** could help clean a weak, distorted signal from a distant rural tower, improving the accuracy of modulation classification and decoding. In essence, the rural environment in Uganda – characterized by long-range links and propagation impediments – underscores the need for robust modulation recognition algorithms that perform reliably under low-SNR, fading conditions (ensuring that even faint signals can be detected and correctly identified by cognitive radio systems).

Sources: World Bank RCIP-5 Report (2022) [6]; GSMA Intelligence via AfricaOne (2025) [11] [12]; Extensia/GSMA (2025) [10]; UCC UCUSAF Program FAQs (2023) [9]; EIB Press Release (2024) [16]; NITA Uganda NBI Report (2019); *KIU/EE Journals* review on rural networks (Thalia 2025) [17] [18].

RF Security Monitoring and Surveillance Needs

Uganda has recognized the importance of **radio frequency (RF) security monitoring** to combat illicit transmissions and protect critical communications. Several cases and policies highlight the need for spectrum surveillance and robust signal classification for national security:

- **Crackdown on illegal broadcasts:** Unauthorized use of the RF spectrum – such as pirate radio stations, rogue telecom operators, or jamming devices – has been a persistent issue. The UCC, as regulator, has ramped up enforcement against illegal transmitters. In late 2018, UCC *deployed an automated spectrum monitoring system* (with remote monitoring stations in Masindi and Mbale) to "crack the whip" on unlicensed broadcasters [19]. This system, implemented with international partners (Central Radio Management Service of S. Korea), **automatically scans and pinpoints illegal radio signals**. *"We want to know who is out there and if they are complying,"* explained UCC's engineering director, noting that **remote monitoring stations ensure the spectrum is well utilized and that illegal operations and interference are minimized** [20]. By switching from ad-hoc manual checks to continuous monitoring, UCC greatly improved its capacity to detect illicit transmissions in real time [21]. The motivation is both economic and safety-related: for instance, Uganda's aviation, emergency services, and telecom operators all rely on clean spectrum, so catching a pirate FM station or an unlicensed two-way radio that could interfere with authorized bands is critical. The UCC's investment (multi-billion UGX) in spectrum monitoring infrastructure shows a strong policy push to secure the airwaves.

- **Spectrum congestion & security:** UCC officials have highlighted that Uganda's RF spectrum is densely populated – *"100% radio coverage"* has been achieved with **over 292 licensed FM radio stations**, plus **20+ providers of voice/data services and ~24 million mobile subscribers**, *"all [using] a finite resource – spectrum – which needs to be managed."* [22]. In this environment, an *illicit transmitter* can easily cause harmful interference (e.g. a bootleg radio station overlapping an airport frequency, or an illegal cellular repeater creating noise on a mobile network). Indeed, many local radio interferences have been traced to stations operating outside their assigned bandwidth or on unauthorized frequencies [23]. By mid-2023 and 2025, UCC intensified crackdowns ("Operation against illegal broadcasters"), even obtaining High Court orders to **shut down pirate radio stations** that reappeared repeatedly. **Security risks:** UCC's legal team warned in 2025 that unlicensed broadcasters pose *"significant risks to public safety, security and the integrity of the country's communications sector."* Because these operators are unregistered, authorities have no record of their location or technical parameters, making it hard to intervene if they air dangerous content or interfere with emergency communications [24]. For example, during national emergencies (e.g. a pandemic or election unrest), the government relies on licensed broadcasters for coordinated messaging; an unregulated transmitter could spread misinformation or disrupt official signals [25]. This underscores a **national security need for robust signal monitoring and identification**. Regulators and security agencies must swiftly detect and classify rogue signals – whether it's a clandestine radio station, a jammer, or an unauthorized military-grade communication – and then take action (e.g. signal jamming or physical confiscation).

- **Electronic warfare preparedness:** Beyond civil spectrum management, the ability to classify and decode RF signals is vital for electronic warfare (EW) and surveillance. Uganda's military and intelligence community (like others globally) monitor the airwaves for threats such as insurgent communications, cross-border illegal transmissions, or hostile drones' control signals. **Automatic Modulation Classification** is a key tool in this domain – originally developed for military SIGINT/COMINT, AMC allows identification of a signal's modulation and thus inference of its type (e.g. distinguishing a military HF encrypted link from a civilian broadcast). A technical survey notes that AMC has long been used in **"military areas such as electronic warfare, surveillance and threat analysis"** [26]. In modern EW receivers, an **AMC module automatically identifies modulation patterns** of intercepted signals, which helps operators decide if a signal is friend, foe, or interference. For Uganda and East African neighbors, regional security challenges (like counter-terror operations in Somalia or illicit radio communications by rebel groups in DRC/South Sudan) mean there is a tangible need for RF signal classification capabilities. Noise-robust AMC, potentially enhanced by Deep Learning (e.g. DAE-based feature extraction), would improve the reliability of **spectrum surveillance systems** used by security agencies. For instance, an SDR-based monitoring station on Uganda's border could use robust AMC to detect a low-power VHF transmission used by smugglers, even under heavy background noise. The **integration of AMC in national spectrum monitoring** thus serves both regulatory enforcement and security intelligence. Uganda's ongoing efforts to modernize police and defense communications (e.g. the Uganda Police's digital radio upgrade to encrypted DMR in 2021) further highlight focus on controlling the RF domain [27] [28]. In summary, documented crackdowns on illegal spectrum use and the stated security concerns show that **monitoring illicit transmissions is a national priority**. Implementing noise-resilient modulation classification in SDR systems will enhance Uganda's ability to **detect, classify, and mitigate unauthorized or threatening RF signals** amidst an increasingly crowded spectrum environment.

Sources: Daily Monitor (UCC), Nov 2018 [19] [20]; UCC Consumer Affairs – Spectrum remarks (2018) [22]; Mulengera News (quoting UCC legal), Aug 2025 [24]; Cutno (2016, p.1) [5]; FOI Sweden Report (2009) [26]; Hytera case study (2021) [27] [28].

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