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Reliability Analysis of Centralized Radio Access Networks in Non-Line-of-Sight and Line-of-Sight Scenarios

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ABSTRACT The fifth generation (5G) wireless network technology is set to be standardized by 2020, where the main goals are to improve capacity, reliability, and energy efficiency while reducing latency and massively increasing connection density. 5G systems target to support a vast number of services with heterogeneous requirements. In recent years, a centralized processing radio architecture called centralized radio access network (C-RAN) or Cloud-RAN has got a lot of attention because of its potential to meet the 5G goals. In this paper, we present a lower layers centric C-RAN analysis methodology, which is designed on the key design principles of 5G systems: *flexibility* and *reliability*. In this paper, *reliability* at lower layers is defined as the probability of achieving a minimum required signal-to-interference-plus-noise-ratio at a user equipment location. The main contributions of our work are the *reliability* analysis of C-RAN systems in non-line-of-sight and line-of-sight conditions. Furthermore, a real-time C-RAN testbed with measurement results are presented to validate the *reliability* analysis.

INDEX TERMS Centralized radio access network (C-RAN), distributed antenna systems (DAS), fifth generation mobile communication (5G), *flexibility*, line-of-sight (LOS), long term evolution (LTE), non-line-of-sight (NLOS), *reliability*, remote radio heads (RRHs), user equipment (UE).

I. INTRODUCTION

Fifth generation (5G) and Beyond wireless network technologies are envisioned to provide services with massive connectivity and coverage, ultra-high data rate, ultra-low latency, improved security, low energy consumption, and outstanding quality of experience (QoE). The general consented set [1] of 5G use cases is, enhanced mobile broadband (eMBB): for supporting very high peak data rates, ultra-reliable low-latency communications (URLLC): for mission critical applications and massive machine-type communications (mMTC): massive connectivity of Internet of Things (IoT) devices.

The key design principles of 5G wireless networks that guide all the requirements in order to serve a broad set of applications are *flexibility* and *reliability* [2]. In 5G systems, *flexibility* is necessary in order to adapt new use cases with a wide range of requirements, which is addressed at architecture level via control plane and user plane separation, programmability across the layers and network slicing based on software defined networking (SDN) [3] principles.

In recent years, a centralized processing approach in radio access network (RAN), called as centralized RAN (C-RAN) or Cloud-RAN [4]–[6] has been proposed by researchers as a potential solution for 5G and Beyond, because of its ability to increase network capacity, coverage and energy-efficiency and manage inter-cell interference [7]. C-RAN typically consists of two parts, a group of distributed remote radio heads (RRHs) and a central unit (CU). The RRHs and CU are interconnected through fronthaul links, which are either dedicated optical cables or Ethernet links. Correspondingly, this idea of distributed antennas has long been existing in the literature as a lower layer technology called Distributed Antenna System (DAS) [8], [9]. Significant work [10], [11] on DAS to understand the advantages and possible deployment strategies of DAS over collocated antenna system (CAS) exists in the literature. Nevertheless, not much work has been done in the area of 5G use cases for C-RAN / DAS in order to derive

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measures for analysis and control of lower layer performance and monitoring of use case requirements in terms of throughput *reliability* and user *fairness*.

The term *reliability* in 5G systems is defined at higher layers as the percentage of sent packets successfully delivered to the destination within the time constraint required by the targeted service. In 5G, for some mission critical use cases belonging to URLLC, the targeted *reliability* is set to 99.999%, which implies that the targeted error probability is set at 10^{-5}. In order to reasonably estimate *reliability* at lower layers, we define *reliability* as the probability of achieving a minimum required SINR of at a UE location. We derive expression for *reliability* in C-RAN / DAS using Rayleigh and Rician Fading channel models, which cover the NLOS [12] and LOS scenarios respectively.

Our main contribution here is the derivation of *reliability* in C-RAN / DAS in LOS conditions using Rician Fading channel Model. In the previous related work [13] existing in the literature, the solution for capture probability in Rician Fading channel considering a minimum required signal-to-interference-ratio (SIR) is derived. We have made use of the methodology of derivation described in [13], to derive the expression for *reliability*.

The rest of the paper is organized as follows: In Section II, the C-RAN / DAS system model is described. In Section III, lower layer *reliability* for C-RAN / DAS in NLOS and LOS conditions is derived. Section IV presents MATLAB based simulation results for the verification of the derived *reliability*, besides providing implementation details of a real-time C-RAN / DAS testbed and measurement results. Section V concludes the paper.

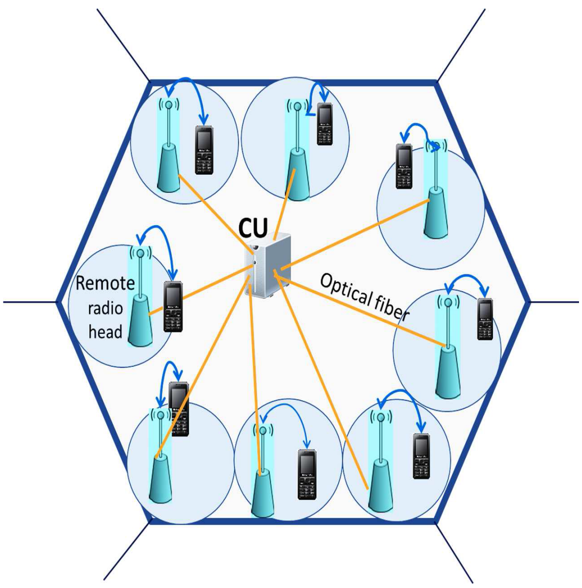


FIGURE 1. C-RAN / DAS system model with distributed RRHs and CU.

II. SYSTEM MODEL

Fig. 1 shows a typical C-RAN / DAS system where the CU does the higher and lower layers processing and sends the baseband signals to the distributed RRHs. The distributed RRHs and CU are interconnected via optical cables using baseband transmission standards like common public radio interface (CPRI) or open base station architecture initiative (OBSAI). The RRHs usually perform as radio frequency (RF) transceivers, but depending on the requirements, RRHs can perform some part of baseband processing as well, in order to decrease the baseband transmission rate through fronthaul links.

For the system model, we consider a scenario which consists of M RRHs and K UEs distributed over the coverage area. Each RRH can have multiple antennas, but here for the sake of simplicity we have considered the case of single antennas at RRHs and UEs. Let UE k, $k \in \{1, 2, .., K\}$, be paired with its nearest RRH called r_k, where $r_k \in \{1, 2, ., M\}$. The received signal at UE k can be expressed as,

$$y_k = h_{k,r_k} x_k + \sum_{r_j \in [1,M], r_j \neq r_k} h_{k,r_j} x_j + z_k, \tag{1}$$

where h_{k,r_j} represents the channel coefficient between UE k and RRH r_j. The transmitted signal from the RRH r_j is represented by x_j. The noise at the receiver of UE k is represented by z_k. The intended signal for UE k is given by x_k, which is transmitted by its paired RRH r_k.

III. RELIABILITY

One of the key design principles of 5G wireless networks is *reliability*. In this work, we define *reliability* at lower layers in terms of probability of achieving a minimum required SINR at a UE location. Usually, the minimum required SINR at a UE location can be derived from conformance requirements set by a communication standard. For example, in 3GPP LTE, the minimum required SINR at UE can be derived from the error vector magnitude (EVM) requirements [14] for different modulation schemes. Similarly, one can deduce the UE's minimum SINR requirement from its different requirements like block error rate (BLER), bit error rate (BER) and average throughput. Based on the minimum SINR requirement, *reliability* can help in monitoring and controlling different UE requirements. Deriving SINR requirements for UEs and employing *reliability* in addressing the following challenges in C-RAN / DAS: pairing of RRHs with UEs, finding frequency reuse pairs, and scheduling of time, frequency and space resources; can improve the system efficiency.

In non-line-of-sight (NLOS) scenarios, the received signal comprises of superimposition of random multipath components arriving at different angles because of reflection, diffraction and scattering in wireless channel. In these scenarios, the received signal amplitude due to multipath fading is closely approximated by Rayleigh fading. In this section, firstly we present *reliability* in C-RAN / DAS in NLOS scenarios [12], considering Rayleigh fading channel model. Secondly, in line-of-sight (LOS) scenarios we derive *reliability* considering Rician fading channel model. In LOS scenarios, the received signal comprises of the stationary dominant LOS signal in addition to the superimposition of random multipath components in wireless channel. The received signal amplitude in these scenarios is closely modeled by Rician Fading. LOS scenarios are more pertinent to real-life scenarios like stadiums, theaters and shopping malls, where the LOS component is dominant.

1) RAYLEIGH FADING

In this subsection, we briefly present *reliability* in NLOS [12]. The probability distribution function of the received power p_r^{k,r_k} at UE k from the RRH r_k in Rayleigh fading channel [12] is given by,

$$f_{P_r}(p_r^{k,r_k}) = \frac{1}{2\gamma_{k,r_k}^2}\exp(-\frac{p_r^{k,r_k}}{2\gamma_{k,r_k}^2}), \tag{2}$$

where $2\gamma_{k,r_k}^2 = P_t^{r_k}K_{FS}(\frac{d_0}{d_{k,r_k}})^\alpha$ represents the mean received power of the signal from the RRH r_k at UE k based on pathloss model. The mean transmitted power of RRH r_k is given by $P_t^{r_k}$, which equals to $E(x_k x_k^*)$, where $E()$ represents the expectation operation. The distance between the RRH port r_k and UE k is given by d_{k,r_k} and α is the path loss exponent. The free-space attenuation constant, assuming an omni-directional antenna, is given by K_{FS} at a reference distance d_0.

In an interference and noise limited system, when N interfering RRHs are transmitting in the same time-frequency resources as that of (UE,RRH) pair (k, r_k), the SINR at k^{th} UE is given by,

$$SINR_{k,r_k} = \frac{p_r^{k,r_k}}{p_N^k + \eta}, \tag{3}$$

where η is the noise power at the receiver and p_N^k is the interference power observed at k^{th} UE from N interfering RRHs. The interference power, p_N^k, can be expressed as $\sum_{r_j\in\{N\},r_j\neq r_k} p_r^{k,r_j}$. Now, *Reliability*, R^k at UE k location, for a minimum required SINR, γ_k, is given by,

$$\begin{aligned} R^k &= P\big(SINR_{k,r_k} \geq \gamma_k\big) = P\bigg(\frac{p_r^{k,r_k}}{p_N^k + \eta} \geq \gamma_k\bigg) \\ &= P\bigg(p^{k,r_k} \geq \gamma_k(p_N^k + \eta)\bigg), \qquad (4) \\ &= E_{P_N^k}\bigg(\int_{\gamma_k(p_N^k+\eta)}^{\infty} A_k^{r_k}\exp\Big(-A_k^{r_k}p_r^{k,r_k}\Big)\,dp^{k,r_k}\bigg), \qquad (5) \end{aligned}$$

where $E_{P_N^k}$ represents the expectation over the interference at k^{th} UE and $A_k^{r_k} = \frac{1}{2\gamma_{k,r_k}^2}$. Since the received interference is independent of the received power from the paired RRH r_k and the interferers are independent as well, (3) can be derived as given in [12] as,

$$R^k = \int_0^\infty \dots \int_0^\infty \exp\Big(-A_k^{r_k}\gamma_k\Big(\sum_{r_j\in[1,M],r_j\neq r_k} p_r^{k,r_j} + \eta\Big)\Big)\prod_{r_j\in[1,M],r_j\neq r_k} f(p_r^{k,r_j})\,dp_r^{k,r_j}. \tag{6}$$

After performing simple integrations the *reliability* at UE k is derived as,

$$R^k(rayleigh) = \exp\Big(-A_k^{r_k}\eta\gamma_k\Big)\prod_{r_j\in[1,M],r_j\neq r_k}\frac{1}{\frac{A_k^{r_k}}{A_k^{r_j}}\gamma_k + 1}. \tag{7}$$

2) RICIAN FADING

In this subsection, we derive *reliability* in case of received signal with LOS component. The probability density function of received signal power based on Rician fading channel is given by [13],

$$f_{P_r}(p_r^{k,r_j}) = \frac{1}{P_{S_{k,r_j}}}\exp(-K_{ri}^{k,r_j})\exp\bigg(-\frac{p_r^{k,r_j}}{P_{S_{k,r_j}}}\bigg) \times I_0\bigg(2\sqrt{K_{ri}^{k,r_j}\frac{p_r^{k,r_j}}{P_{S_{k,r_j}}}}\bigg), \tag{8}$$

where $K_{ri}^{k,r_j} = \frac{P_{D_{k,r_j}}}{P_{S_{k,r_j}}}$ is the Rician factor and $I_0(\ )$ is the modified Bessel function of first kind and zero order [15]. In this channel model, the total mean power received at UE k is equal to sum of the average power received by the LOS component, $P_{D_{k,r_j}}$, and mean of total received power over the scattered paths, $P_{S_{k,r_j}}$. According to the pathloss model, the sum of the mean received powers via LOS and NLOS is given by,

$$P_{D_{k,r_j}} + P_{S_{k,r_j}} = P_t^{r_j}K_{FS}(\frac{d_0}{d_{k,r_j}})^\alpha. \tag{9}$$

Let $A_k^{r_k} = \frac{1}{P_{S_{k,r_k}}}$ and $B_k^{r_k} = \frac{K_{ri}^{k,r_k}}{P_{S_{k,r_k}}}$, then the pdf of the received signal power at UE k due to RRH r_k is represented by,

$$f_{P_r}(p_r^{k,r_k}) = A_k^{r_k}\exp(k, r_k)\exp\Big(-A_k^{r_k}p_r^{k,r_k}\Big) \times I_0\Big(2\sqrt{B_k^{r_k}p_r^{k,r_k}}\Big). \tag{10}$$

The *reliability*, R^k, at k^{th} UE location for a minimum SINR required, γ_k, where UE k is paired to RRH r_k and having N number of interfering RRHs is given by,

$$\begin{aligned} R^k &= P\bigg(SINR_{k,r_k} \geq \gamma_k\bigg) = P\bigg(\frac{p_r^{k,r_k}}{p_N^k + \eta} \geq \gamma_k\bigg) \\ &= P\bigg(p_N^k \leq \frac{p_r^{k,r_k}}{\gamma_k} - \eta\bigg) \\ &= \int_0^\infty\bigg(\int_0^{(\frac{p_r^{k,r_k}}{\gamma_k}-\eta)} f_{P_N^k}(p_N^k)\,dp_N^k\bigg) f_{P_r}(p_r^{k,r_k})\,dp_r^{k,r_k}. \end{aligned} \tag{11}$$

The double integral in (11) can be solved by changing the order of integration as,

$$R^k = \int_0^\infty\bigg(\int_{(p_N^k+\eta)\gamma_k}^\infty f_{P_r}(p_r^{k,r_k})dp_r^{k,r_k}\bigg) f_{P_N^k}(p_N^k)\,dp_N^k. \tag{12}$$

At first we solve the inner integral in (12), which results in,

$$\int_{(p_N^k+\eta)\gamma_k}^{\infty} f_{P_r}(p_r^{k,r_k})dp_r^{k,r_k} = A_k^{r_k}\exp(-K_{ri}^{k,r_k}) \times \sum_{n=0}^{\infty}\frac{(B_k^{r_k})^n}{(n!)^2}\int_{(p_N^k+\eta)\gamma_k}^{\infty}(p_r^{k,r_k})^n\exp(-A_k^{r_k}p_r^{k,r_k})dp_r^{k,r_k} = \exp\big(-K_{ri}^{k,r_k}\big)\sum_{n=0}^{\infty}\frac{(K_{ri}^{k,r_k})^n}{(n!)^2}\Gamma\big(n+1, A_k^{r_k}(p_N^k+\eta)\gamma_k\big), \tag{13}$$

where $\Gamma(a,b)$ is the upper incomplete gamma function, which can be expressed as series expansion according to [15] as,

$$\Gamma\big(n+1, A_k^{r_k}(p_N^k+\eta)\gamma_k\big) = \Gamma(n+1)\exp\big(-A_k^{r_k}(p_N^k+\eta)\gamma_k\big)\sum_{k=0}^{n}\frac{(A_k^{r_k}(p_N^k+\eta)\gamma_k)^k}{k!}. \tag{14}$$

Using the result from (14) in (13) gives the solution for the inner integral of (12) as,

$$\int_{(p_N^k+\eta)\gamma_k}^{\infty} f_{P_r}(p_r^{k,r_k})dp_r^{k,r_k} = \exp\big(-K_{ri}^{k,r_k}\big) \times \exp\big(-A_k^{r_k}\eta\gamma_k\big)\sum_{n=0}^{\infty}\frac{(K_{ri}^{k,r_k})^n}{n!}\sum_{m=0}^{n}\frac{(A_k^{r_k}\gamma_k)^m}{m!} \times \exp(-A_k^{r_k}p_N^k\gamma_k)(p_N^k+\eta)^m. \tag{15}$$

In order to solve the pdf of p_N^k, which is sum of the received powers at UE k from N reuse RRHs assuming Rician fading channel model for all the interfering channels. For the sake of simplicity of derivation, we assume all the interfering RRHs are placed equidistantly to the UE k and equal transmit powers from RRHs. In this case, the probability density function of p_N^k is solved in [13] to be,

$$f_{P_N^k}(p_N^k) = \exp(-NK_{ri}^{k,N})\exp\big(-(A_N^k)^N\big)\Big(\frac{1}{NB_N^k}\Big)^{\frac{N-1}{2}} \times (p_N^k)^{\frac{N-1}{2}} I_{N-1}\big(2\sqrt{NB_N^k p_N^k}\big), \tag{16}$$

where I_{N-1} is the modified $N-1^{th}$ order Bessel function of first kind. Using the series expansion of I_{N-1} [15], (16) can be expressed as,

$$f_{P_N^k}(p_N^k) = \exp(-NK_{ri}^{k,N})(A_N^k)^N\exp(-A_N p_N^k\gamma_k) \times \sum_{l=0}^{\infty}\frac{(NB_N^k)^l}{l!\Gamma(l+N)}(p_N^k)^{l+N-1}. \tag{17}$$

Using the results from (15) and (17) in (12), results in,

$$R^k = \exp\big(-(NK_{ri}^{k,N}+K_{ri}^{k,r_k})\big)\exp(-A_k^{r_k}\eta\gamma_k)(A_N^k)^N \times \sum_{n=0}^{\infty}\frac{(K_{ri}^{k,r_k})^n}{n!}\sum_{m=0}^{n}\frac{(A_k^{r_k}\gamma_k)^m}{m!}\sum_{l=0}^{\infty}\frac{(NB_N^k)^l}{l!\Gamma(l+N)} \times \int_0^{\infty}\exp(-p_N^k(A_k^{r_k}\gamma_k+A_N^k)(p_N^k)^{m+l+N-1}\Big(1+\frac{\eta}{p_N^k}\Big)^m dp_N^k. \tag{18}$$

Since in practical cellular scenarios, the received interference power p_N^k is much greater than noise power η, the integral in (18) can be approximated according to [15] as,

$$\frac{1}{(A_k^{r_k}\gamma_k+A_N^k)^{m+l+N}}\Gamma(m+l+N). \tag{19}$$

Now, using the result from (19) in (18) derives the *reliability* for LOS scenarios, which is given by,

$$R^k(rician) = \exp\big(-(NK_{ri}^{k,N}+K_{ri}^{k,r_k})\big)\exp(-A_k^{r_k}\eta\gamma_k) \times \sum_{n=0}^{\infty}\frac{(K_{ri}^{k,r_k})^n}{n!}\sum_{m=0}^{n}\left(\frac{A_k^{r_k}}{A_N^k}\right)^m\frac{(\gamma_k)^m}{m!\left(\frac{A_k^{r_k}}{A_N^k}\gamma_k+1\right)^m} \times \sum_{l=0}^{\infty}\frac{(NK_{ri}^{k,N^k})^l}{l!}\frac{1}{\left(\frac{A_k^{r_k}}{A_N^k}\gamma_k+1\right)^{l+N}}\frac{\Gamma(m+l+N)}{\Gamma(l+N)}. \tag{20}$$

As a corollary, if $K_{ri}^{k,N}=0$, $K_{ri}^{k,r_k}=0$ and the interfering RRHs are equidistant to UE k, the $R^k(rician)$ in (20) and $R^k(rayleigh)$ in (7) becomes equal to that of NLOS scenario, which is given by,

$$R^k(rician) = R^k(rayleigh) = \exp(-A_k^{r_k}\eta\gamma_k)\frac{1}{\left(\frac{A_k^{r_k}}{A_N^k}\gamma_k+1\right)^N}. \tag{21}$$

IV. RESULTS

A. SIMULATION MODEL

The derived *reliability* in Section III, which are Eq. (7) and Eq. (20), are validated using extensive Monte-Carlo simulations in MATLAB using Rayleigh and Rician distribution empirical models provided by MATLAB. We have verified the derived *reliability* extensively by varying the number of RRHs, UE locations and SINR requirements. We have observed perfect match between MATLAB based empirical models and derived expressions, which implies that the error is less than 10^{-5}. Hence the correctness of the derivations is verified.

To evaluate the *reliability*, we have considered an UE k with 6 equidistantly placed interferers, and all the RRHs are transmitting equal power. We have assumed that the interferers are located at a distance of 7 times the RRH coverage radius from the UE k location, which implies that the interferers are adequately distant to reuse the time frequency resources of UE k. At first we investigate the effect of LOS components of the interfering and desired signals on the *reliability*, and later we present the effect of interferers distance on the *reliability*.

In Fig. 2, we have simulated a case where the Rician factor of each interfering channels are set, $K_{ri}^{k,N} = -\infty$, and the Rician factor K_{ri}^{k,r_k} desired signal at UE k varies between $-\infty$ to 12 dB. NLOS scenario is represented by the Rician factor being $-\infty$ and Rician factor of 12 dB represents a very strong LOS signal. From the results we can observe that, for a practical *reliability* level of 0.8, the minimum required SINR at a UE location increases from 11 dB to 16 dB, as the power in LOS component increases. This scenario has a direct practical relevance for C-RAN / DAS in shopping malls. In shopping malls, the probability of receiving LOS signal from serving RRH is significantly higher than that of interfering signals because of many obstructions.

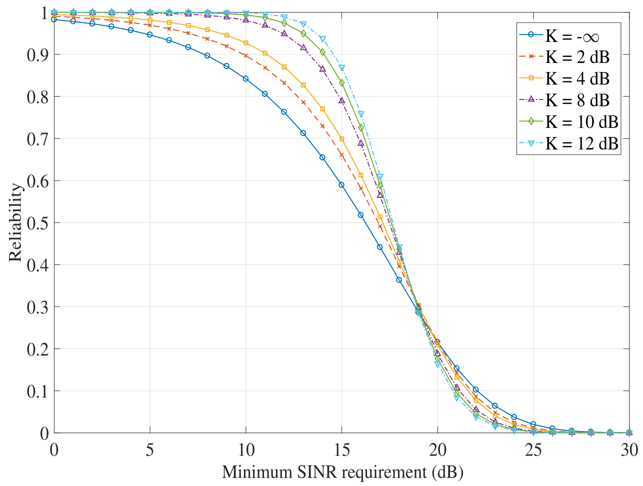


FIGURE 2. Reliability in case of $K_{ri}^{k,N} = -\infty$, varying K_{ri}^{k,r_k}.

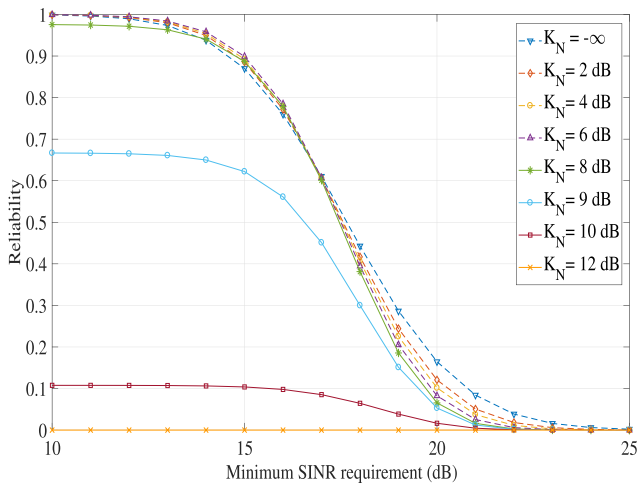


FIGURE 3. Reliability in case of $K_{ri}^{k,r_k} = 12$dB, varying $K_{ri}^{k,N}$.

Fig. 3 represents the impact of interferer's LOS component on the reliability of UE k, which has a strong LOS component (12 dB) from its serving RRH. This scenario occurs in open dense public places like stadiums and concerts. As shown in the figure, *reliablity* is not much affected due to increase in the intensity of LOS components of the interfering signals until a certain level, which is around 8 dB. But, when intensity of LOS components of the interfering signals is above 9 dB, its impact on the reliability of UE k is significant, which makes it non-practical to reuse the time-frequency resources with the interfering RRHs. Hence *reliability* can provide statistically a good insight in these scenarios for RRH placements and finding frequency reuse opportunities.

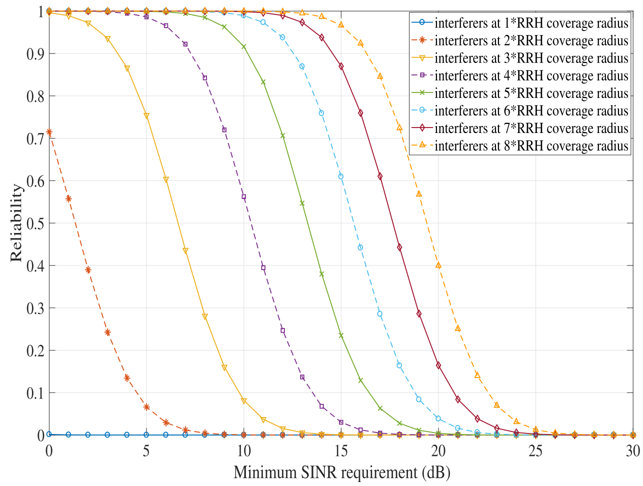


FIGURE 4. Reliability in case of varying the distances of interferers, with $K_{ri}^{k,r_k} = 12$dB, $K_{ri}^{k,N} = -\infty$.

Fig. 4 shows the effect of varying the distances of interferers on the *reliability* of UE k. When the interfering power is exactly equal to the desired signal power, the *reliability* is 0. But, for all other cases there is always some achievable *reliability* at different SINR levels at UE location. This can be exploited by the formation of dynamic frequency reuse RRH groups. Since in a practical wireless system, different UEs have different throughput and reliability requirements, the results here show the possibilities of forming dynamic frequency reuse RRH groups, thereby improving the system throughput and as well meeting the varied requirements of UEs.

Furthermore, at lower layers, *reliability* provides a statistical estimate of the system *reliability*, which is one of the key capabilities defined in 5G. In some mission critical applications belonging to 5G URLLC usecase, the *reliability* requirement is set to a very high value, which is $1 - 10^{-5}$ [2]. As shown in the results from different scenarios, the minimum SINR requirement at the device location can be determined based on the location of the device, transmitted powers, reliability requirement and LOS components strengths. In order to achieve the minimum SINR requirement of these mission critical applications, MAC scheduler can effectively schedule time, frequency and power resources among the devices or users reusing the same time-frequency resources. Therefore, *reliability* addresses the lower layer key capability requirement of 5G systems, besides providing minimum SINR requirements of different users and devices, which can significantly help in reliable and efficient scheduling of resources.

B. REAL-TIME C-RAN / DAS TESTBED

In this section, we present the hardware and implementation details of real-time LTE based C-RAN / DAS testbed implemented on software defined radio (SDR) platform, which is an extension of our previous related work [12].

As shown in Fig. 5 central unit (CU) is implemented on DSP and ARM boards. TI's TMS320C6670 DSP is a multicore fixed-point processor for small cell eNodeB physical (PHY) layer processing with suitable hardware accelerators. PHY layer processing runs on the DSP. The DSP communicates with MAC and higher layers, which are running on an ARM CORTEX A9 board via Gigabit Ethernet interface. The LTE based C-RAN / DAS testbed is fully functional to attach many commercial UEs and to communicate with them.

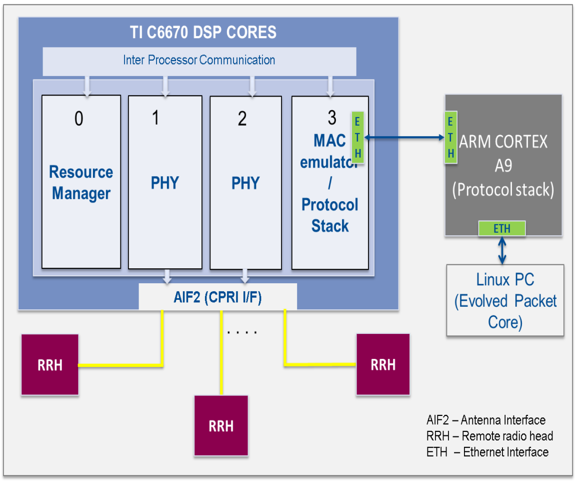


FIGURE 5. Hardware Implementation blocks.

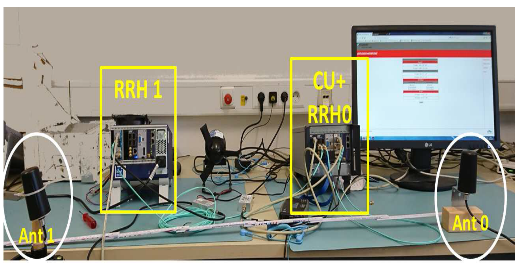


FIGURE 6. LTE based C-RAN / DAS CU with 2 RRHs.

Fig. 6 and Fig. 7 show the real-time C-RAN / DAS testbed and Keysight's MXA signal analyzer with 89600 VSA software for LTE PHY layer analysis. The 89600 VSA software provides in-depth analysis of LTE system performance of each decoded channels. The *reliability* is validated by, scheduling of overlapping RB allocation for 2 UEs, and by varying UE and RRH placements and measuring their effect on the received signal quality. The received signal quality for downlink channels is measured by 89600 VSA software, which is running on Keysight's MXA signal analyzer,

FIGURE 7. Measurement equipment - 89600 VSA software on Keysight MXA.

TABLE 1. LTE configuration.

Parameters	Values
Carrier frequency DL	2.655 GHz
Channel bandwidth DL	10 MHz / 50 RBs
No. of UEs	2
No. of RRHs	2
No. of antennas per RRH	1 (SISO)
No. of RBs scheduled in DL for UE1	50 RBs / all RBs
No. of RBs scheduled in DL for UE2	50 RBs / all RBs
Max. Tx. Power RRH0	-8 dBm
Max. Tx. Power RRH1	-8 dBm
RNTI of UE1	10
RNTI of UE2	20

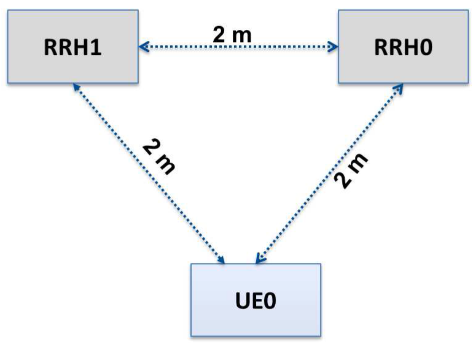
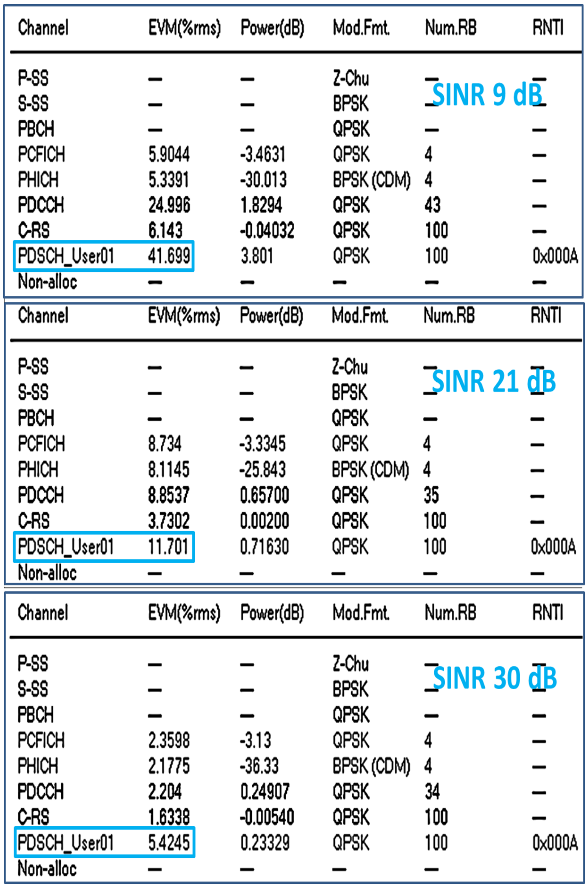


FIGURE 8. Measurement scenario with 2 RRHs.

in terms of error vector magnitude (EVM). Table 1 below provides the LTE parameters configured for our investigations.

The EVM is defined in 3GPP LTE [14] as a measure of the difference between the ideal constellation points and the measured points after channel equalization. This difference is called the error vector. The EVM result is defined as the square root of the ratio of the mean error vector power to the mean reference power expressed in percent. In LTE the minimum required EVM for different modulation schemes is defines as: 18.5% for QPSK, 13.5% for 16 QAM and 9% for 64QAM. Since SINR (dB) = -20log10(EVM), these EVM requirements correspond respectively to SINR requirements of: 14.6 dB, 17.4 dB and 20.9 dB, for QPSK, 16 QAM and 64 QAM modulation schemes. Hence, the EVM requirements provide an good estimate in determining the minimum required SINR for *reliability*.



SINR 9 dB

Channel	EVM(%rms)	Power(dB)	Mod.Fmt.	Num.RB	RNTI
P-SS	–	–	Z-Chu	–	–
S-SS	–	–	BPSK	–	–
PBCH	–	–	QPSK	–	–
PCFICH	5.9044	-3.4631	QPSK	4	–
PHICH	5.3391	-30.013	BPSK (CDM)	4	–
PDCCH	24.996	1.8294	QPSK	43	–
C-RS	6.143	-0.04032	QPSK	100	–
PDSCH_User01	41.699	3.801	QPSK	100	0x000A
Non-alloc	–	–	–	–	–

SINR 21 dB

Channel	EVM(%rms)	Power(dB)	Mod.Fmt.	Num.RB	RNTI
P-SS	–	–	Z-Chu	–	–
S-SS	–	–	BPSK	–	–
PBCH	–	–	QPSK	–	–
PCFICH	8.734	-3.3345	QPSK	4	–
PHICH	8.1145	-25.843	BPSK (CDM)	4	–
PDCCH	8.8537	0.65700	QPSK	35	–
C-RS	3.7302	0.00200	QPSK	100	–
PDSCH_User01	11.701	0.71630	QPSK	100	0x000A
Non-alloc	–	–	–	–	–

SINR 30 dB

Channel	EVM(%rms)	Power(dB)	Mod.Fmt.	Num.RB	RNTI
P-SS	–	–	Z-Chu	–	–
S-SS	–	–	BPSK	–	–
PBCH	–	–	QPSK	–	–
PCFICH	2.3598	-3.13	QPSK	4	–
PHICH	2.1775	-36.33	BPSK (CDM)	4	–
PDCCH	2.204	0.24907	QPSK	34	–
C-RS	1.6338	-0.00540	QPSK	100	–
PDSCH_User01	5.4245	0.23329	QPSK	100	0x000A
Non-alloc	–	–	–	–	–

FIGURE 9. EVM measurement results for QPSK with varying SINR.

Fig. 8 shows the measurement scenario where the two RRHs are 2 m apart from each other and the UE, which is an LTE measurement equipment, is placed 2 m apart from each of the RRHs. In this scenario, the same time-frequency resources are reused by the 2 RRHs. The transmit power level of RRH0 is kept constant and the transmit power level of RRH1 is varied in order to vary the SINR at UE location. In case of QPSK modulation configured using the MCS values mentioned in Table 1, the measured EVM results of all the channels including PDSCH are shown in Fig. 9. It is measured that in case of QPSK, the minimum required SINR level is 15 dB in order to meet the LTE requirement. Similarly we have measured that the minimum required SINR to be 21 dB in case of 16 QAM. The measurement results correspond to *reliability* analysis presented in this paper.

V. CONCLUSION

In this paper, we have presented lower layers centric C-RAN/ DAS analysis based on *reliability*, which is one of the key design principles of 5G systems. In this work, we have derived *reliability* in C-RAN / DAS, as the probability of achieving a minimum required SINR at a UE location. The *reliability* in NLOS scenarios using Rayleigh fading models and LOS scenarios using Rician fading channel model is derived. We have verified and validated our derivations using MATLAB simulation models. Through simulation results, we have shown how the intensity of LOS component of interferers and desired signals effects the *reliability*. In this regard, we have analyzed the simulation results in the view of realistic C-RAN / DAS deployment scenarios like stadiums and shopping malls, besides presenting the benefits of *reliability* analysis. A LTE based Real-time C-RAN / DAS testbed with measurement results of *reliability* and minimum SINR requirements is presented.

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