Authors' version of the paper that appears in the proceedings of 2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW 2019)
DOI: 10.1109/WCNCW.2019.8902898

Dynamic Radio Frame Configuration by Exploiting Uplink Control Channel for URLLC

Navuday Sharma *, Muhammad Mahtab Alam*, Yannick Le Moullec*,
Hassan Malik*, Mehdi Bennis† and Sven Pärand‡
*Thomas Johann Seebeck Department of Electronics, Tallinn University of Technology, Tallinn, Estonia
†Centre for Wireless Communications, University of Oulu, Oulu, Finland
‡Telia Estonia Ltd, Tallinn, Estonia
navuday.sharma@taltech.ee, muhammad.alam@taltech.ee, yannick.lemoullec@taltech.ee,
hassan.malik@taltech.ee, mehdi.bennis@oulu.fi and sven.parand@telia.ee

***Abstract*— uRLLC (ultra-Reliable Low Latency Communications) requires a new paradigm in 5G cellular networks to satisfy extreme latency and reliability thresholds. Further, such constraints have a wide range due to different use case scenarios. Consequently, how to configure suitable radio frame structure that matches to the latency and reliability requirements of the given use-case is an open question. This article addresses the above-mentioned issue and provides a preliminary investigation and a feasible solution by exploiting antenna port selection index (APSI) calculated using fuzzy logic algorithm, which is further communicated through physical uplink control channel. Closed-form expressions of outage probability for the number of users, under given latency and reliability constraints have been provided with the mathematical proof and the results were simulated based on the prior availability of APSI. It is shown that outage probability improves up to 30% in case of dynamic radio frame configuration.**

***Index Terms*— URLLC, Outage Probability, Closed-Form Expressions, Fuzzy Logic, Antenna Port Selection Index, Dynamic Radio Frame, Uplink Control Channel Design.**

I. INTRODUCTION

THE 5^{th} generation of cellular technology has three pillars envisioned to support the wide variety of services provided to 5G New Radio (NR) users: eMBB (enhanced-Mobile Broadband), mMTC (massive-Machine Type Communications) and uRLLC (ultra-Reliable Low Latency Communications) with several technologies. References [1]–[3] provide details of such technologies, challenges and proposed solutions to fulfill the requirements of 5G users. Among these, uRLLC is meant to support applications requiring very low latency and higher order of reliability as compared to 4G systems. Current 4G systems target a nominal latency of 15 ms or above with target Block Error Rate (BLER) of 10^{-2} [4]. Moreover, the present systems are optimized for mobile broadband traffic. On the contrary, 5G NR under uRLLC envisages the latency to be 1 ms or lower with a stringent reliability of BLER as low as 10^{-9}. Reference [5] provides details about uRLLC services and requirements.

There are several design challenges for achieving uRLLC, such as short transmission time interval (TTI), fast hybrid automatic repeat request (HARQ) re-transmissions, link adaption for control channels, channel quality indicator enhancements, diversity, grant-free access, etc. Further details regarding the mentioned challenges are addressed in [6]. One of the key aspects to support uRLLC is the re-thinking and modification of classical assumptions in communication theory, for example, re-structuring the radio frame for data and control channels, change in network topology and access protocols, etc. In [7], such principles are considered and discussed. With such a new set of assumptions for uRLLC, many trade-offs in terms of reliability and latency with key performance metrics such as spectral efficiency, user device energy, signal to noise ratio, etc. are bound to be expected. Reference [4] addresses such trade-offs and also provides key enablers for uRLLC, such as packet duplication, edge caching, link adaptation, network slicing etc, with potential risks and scaling to millions of devices.

There are several conceivable use cases that can benefit from uRLLC with requirements of low latency and high reliability [9]. For example, the healthcare sector with various medical and non-medical applications [10], telesurgery which includes remote surgery through a robotic arm enabled with haptic feedback [11], the tactile internet scenario requiring end-to-end latency lower than 1 ms and extremely high BLER of 10^{-9}, being a safety critical application. Further, ITS (Intelligent Transportation System) with vehicles cooperating with each other and local access points to mitigate complex road or aerial situations [12], require comparatively higher order reliability and latency constraints. Similarly, factory control in smart industry [13], enabling machines to communicate through a cellular network require a different order of these constraints, depending on the type of industry as well. A detailed description regarding the use cases is discussed in [14]. Therefore, based on the use case, the requirements for uRLLC vary. The Third Generation Partnership Project (3GPP) has recently provided a study on the enhancement of the Physical Layer (PHY) for NR in uRLLC [8]. Further, enhancements for uRLLC support in the 5G Core network are addressed in [15], where key issues and solutions are proposed. The standardization procedure has been divided into two phases: the fundamental specifications for 5G NR were approved in Release 15 by the end of 2017, with initial feasibility studies and a definition of performance metrics initiated in Release 14. Further, enhancements in the

TABLE I: Use Cases for 3GPP Rel-16 NR uRLLC evaluation [8]

Use Case	**Reliability (%)**	**Latency**	**Data Packet Size and Traffic Model**
Power Distribution	99.9999	5 ms (end to end latency), where 2-3 ms is air interface latency	DL and UL: 100 bytes. FTP model 3 with arrival interval 100 ms
	99.999	15 ms (end to end latency), where 6-7 ms air interface latency	DL and UL: 250 bytes Periodic and deterministic with arrival interval 0.833 ms. Random offset between UEs
Factory automation	99.9999	2 ms (end to end latency), where 1 ms is the air interface latency	DL and UL: 32 bytes. Periodic deterministic traffic model with data arrival interval 2 ms
Augmented/Virtual reality	99.999	1 ms (air interface delay) for 32 bytes 1 ms and 4 ms (air interface delay) for 200 bytes	DL and UL: 32 and 200 bytes FTP model 3. Periodic with different arrival rates
	99.9	7 ms (air interface delay)	DL and UL: 4096 and 10 K bytes FTP model 3 or periodic with different arrival rates
Transport Industry	99.999	5 ms (end to end latency), where 3 ms is the air interface latency	UL- 2.5 Mpbs; Packet size 5220 bytes and DL- 1Mbps; Packet size 2083 bytes. Note that the data arrival rate is 60 packets per second for periodic traffic model
	99.999	10 ms (end to end latency), where 7ms is the air interface latency	UL and DL- 1.1 Mbps; Packet size 1370 bytes. Note that the data arrival rate is 100 packets per second for periodic traffic model

specifications will be completed in Release 16 by the end of 2019 and would be submitted to International Telecommunication Union (ITU) by 3GPP [16].

II. Motivation and Contribution

The major issue in uRLLC is to meet such stringent latency and reliability requirements, with efficient resource allocation to reduce BLER and round trip time (RTT). To address this issue, uplink control channel design is important [17], to ensure reliable delivery of the scheduling request (SR), resource grant (RG) and channel quality indicator (CQI), to improve reliability and flexible slot structures in the radio frame, in order to reduce the latency. Also, since the number of use case scenarios is high, ensuring the uRLLC constraints for each of them is a challenging issue.

There are only a few contributions to the enhancement of the Physical Uplink Control Channel (PUCCH) for uRLLC, which has been highlighted as one of the key issues under PHY enhancements by 3GPP in Release 16 [8]. In [18], the authors focus on the shortened PUCCH (sPUCCH) based on reducing the TTI, approved by the Radio Access Network (RAN) Work Group 1 in the study item of 3GPP [19]. In sPUCCH design, the number of Single Carrier - Frequency Division Multiple Access (SC-FDMA) symbols are reduced to 2-3. Further, frequency hopping in the same subframe is used to improve reliability, while maintaining the latency constraint. Also, a sequence based sPUCCH structure is proposed to mitigate the lower coverage problem arising from reducing the number of symbols in the TTI. In [20] design methods of various PUCCH formats in NR depending on the number of bits to be transmitted, are presented. Similarly, [21] proposes different types of sPUCCH designs to reduce the number of transmission bits.

However, none of the works in the existing literature address the issue of latency and reliability constraints being dependent on the type of use cases (see Table I for some examples). Therefore, instead of implementing a fixed numerology of a radio frame in NR, a dynamic radio frame structure, based on latency and reliability values, seems a feasible option for uRLLC. To the best of our knowledge, this is the first article to propose this concept and methodology for its implementation via uplink control channel. To enable a dynamic radio frame, we propose to implement an antenna port selection index (APSI), which maps the antenna ports to users in various use cases for allocating different radio frames. Additionally, the outage probability, based on latency and reliability constraints is calculated and simulation results are provided with and without prior APSI information.

The article is organized as follows. Section III provides the fuzzy logic approach to implement a dynamic radio frame to accommodate various use cases with stringent latency and reliability constraints. In Sec. IV, outage probability for the number of users under uRLLC constraints is formulated and simulated with the proofs of the analytical expressions. Finally, the paper is concluded in Sec. V.

III. System Model to obtain Dynamic Radio Frame Configuration

To enable dynamic radio frame structure in uRLLC, prior information regarding latency and reliability should be given to the base station to allocate the radio resources based on the user equipment (UE) requirement depending on PUCCH format [20], which further depends on the use case scenario. To accomplish this, three steps have been provided for the proposed algorithm:

- *Setting up the UE for use case scenario:* Since there are multiple use case scenarios in uRLLC, the UEs under specific use cases should be differentiated. Further, a maximum threshold for the latency = α and reliability = β should be defined for the UEs.

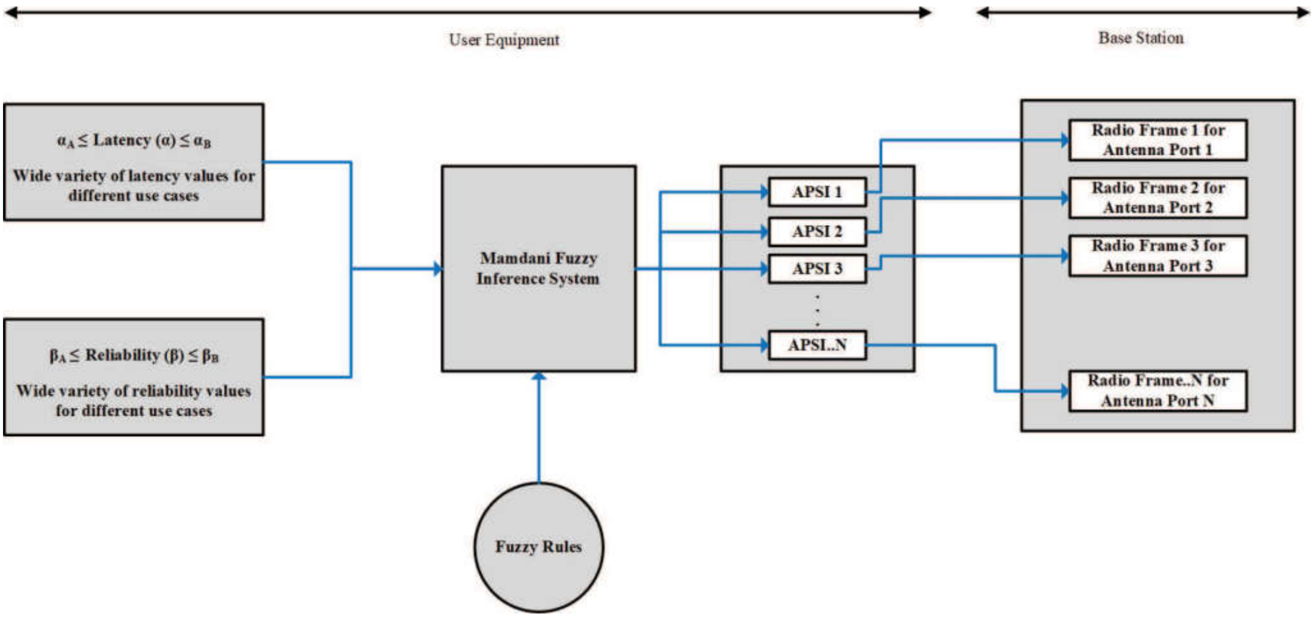

Fig. 1: System Model for obtaining Dynamic Radio Frame Configuration from APSI transmitted by UE in the uplink via physical uplink control channel.

- *Fuzzy Logic Operation:* The fuzzy logic approach is implemented to obtain the APSI for the UEs under different use cases, as shown in Fig. 1. Antenna ports are logical entities transmitting one resource grid. Multiple antenna ports can be supported by a physical antenna, depending on the reference signal configuration in the cell [22]. Here, fuzzy logic is deemed as the best probable approach to develop the system model since precise boundaries for the latency and reliability requirements are too rigid for some use cases like tele-surgery and also are not available yet for many other use cases. In fuzzy operation, latency and reliability are given as inputs to the Mamdani-based [23] fuzzy inference system and APSI is obtained as the output. Later, membership functions to perform fuzzy calculations have been assumed for latency and reliability as Gaussian as shown in Fig. 2, classifying them from lowest to highest, due to unavailability of the training data and measurement campaigns for uRLLC and to enable smooth variation of the constraints. However, a triangular membership function was preferred for APSI to obtain an independent and identically distributed index. Additionally, nine rules have been defined in the Mamdani system to obtain the APSI, based on the structure: "*If latency is $alpha$ and reliability is β the APSI is γ.*" Table II defines the rules implemented accordingly. Lastly, the fuzzy sets of data were defuzzified using centroid method and the APSI information was obtained, from latency and reliability constraits, as shown in Fig. 3.
- *Dynamic Radio Frame Configuration:* The prior APSI information obtained is transmitted to the base station via uplink control channel. The base station dynamically configures the radio frame by allocating the UEs to the desired radio frame for the downlink transmission, which is pre-configured on the antenna port of the base station for different use cases.

TABLE II: Implemented rules for fuzzy inference system

Latency (α)	Reliability (β)	APSI (γ)
low	low	index A
low	medium	index B
low	high	index C
medium	low	index D
medium	medium	index E
medium	high	index F
high	low	index G
high	medium	index H
high	high	index I

Fig. 1 shows the system model enabling above defined procedures. The proposed approach should have better results since each antenna port is presumed to have a dedicated radio frame to provide a service for a specific use case.

IV. Outage Probability under Latency and Reliability Constraints

In this section, we provide the outage probability P_{out} for the number of users in outage, given the latency and reliability constraints in different use case scenarios. Here, two expressions of P_{out} are provided, whose proofs are available in a later section. Firstly, the expression without prior APSI index information is given as

$$P_{out}(\alpha,\beta) = 1 - P(X_A < \alpha, X_B > \beta) \tag{1}$$

where, X_A and X_B are random variables denoting latency and reliability, respectively. Thresholds *i.e*, α for latency and β for reliability are provided, which can vary depending on

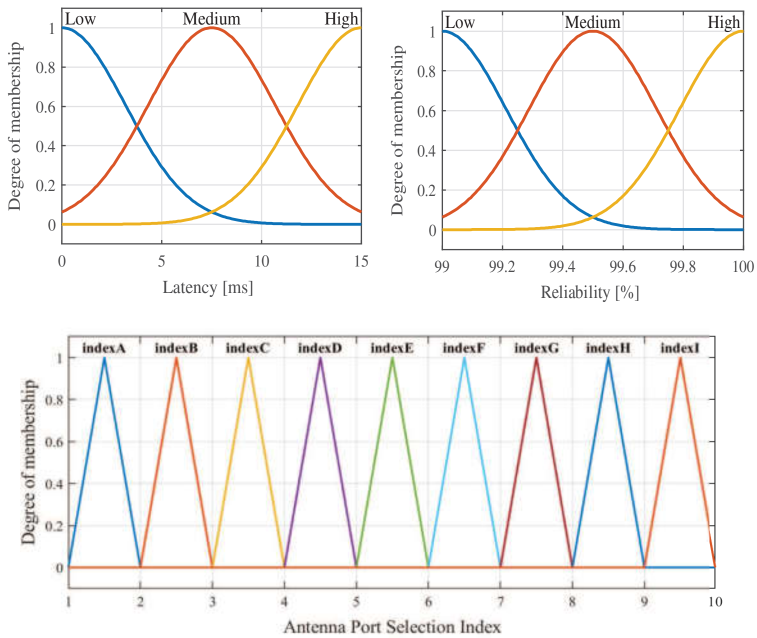

Fig. 2: Membership functions for latency, reliability and APSI in fuzzy inference system.

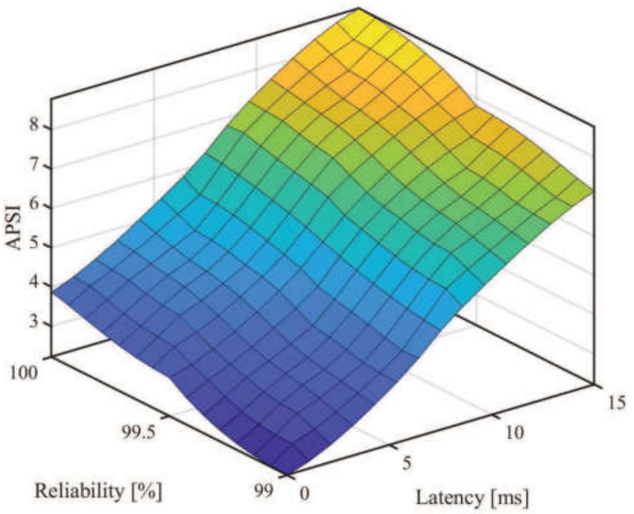

Fig. 3: APSI allocation based on latency and reliability constraints.

the use case scenario; erf is the error function. $P(X_A < \alpha, X_B > \beta)$ represents the joint probability when latency and reliability are under specific thresholds. After analytical formulation, the final expression for P_{out} is given in Eq. (2) as

$$P_{out}(\alpha_A,\beta_A,\beta_B) = 1 - \left[\frac{1}{2}erf\left(\frac{\alpha_A}{\sqrt{2}}\right)\left[\frac{1}{2}erf\left(\frac{\beta_B}{\sqrt{2}}\right) - \frac{1}{2}erf\left(\frac{\beta_A}{\sqrt{2}}\right)\right]\right] \quad (2)$$

where, α_A, β_A and β_B are the lower and upper limits of latency and reliability, respectively, for a given use case. From Eq. (1) and (2), P_{out} depends on latency and reliability thresholds, when APSI index information is not available. Further, P_{out} with known APSI information, is given as

$$P_{out}(\alpha,\beta) = 1 - P(X_{A|\gamma=y} < \alpha, X_{B|\gamma=y} > \beta) \quad (3)$$

where, γ represents APSI. The expression $P(X_{A|\gamma=y} < \alpha, X_{B|\gamma=y} > \beta)$ denotes the conditional probability that latency and reliability are under desired thresholds, given that γ is provided as y. After mathematical analysis, the desired expression is obtained as

$$P_{out}(\alpha_A,\beta_A,\beta_B) = 1 - \left[\frac{\pi}{2}erf\left(\frac{\alpha_A}{\sqrt{2}}\right)\sqrt{\frac{\pi}{2}}erfi\left(\frac{X_A}{\sqrt{2}}\right)\right] \left[\frac{1}{2}erf\left(\frac{\beta_B}{\sqrt{2}}\right) - \frac{1}{2}erf\left(\frac{\beta_A}{\sqrt{2}}\right)\right]\sqrt{\frac{\pi}{2}}erfi\left(\frac{X_B}{\sqrt{2}}\right)\Bigg] \quad (4)$$

where $erfi$ is the imaginary error function. The outage probability, i.e, the probability of users not satisfying the constraints of latency and reliability are shown in Fig. 4. Here, it can be observed that a generally significant improvement in outage can be obtained if prior APSI is known. We consider to exploit uplink control channel which can communicate APSI to the base station in order to execute dynamic radio frame configuration.

It is observed that the improvement in outage is less significant at lower latency values, however, we are still able to get about 15% gain closer to 0ms and 20% at 1ms. It can be noticed that as the latency constraint is relaxed, more significant improvement can be observed and maximum gain achieved can be up to 30% . A similar graph was obtained with reliability as constraint, since it was statistically modeled, as seen in the proofs.

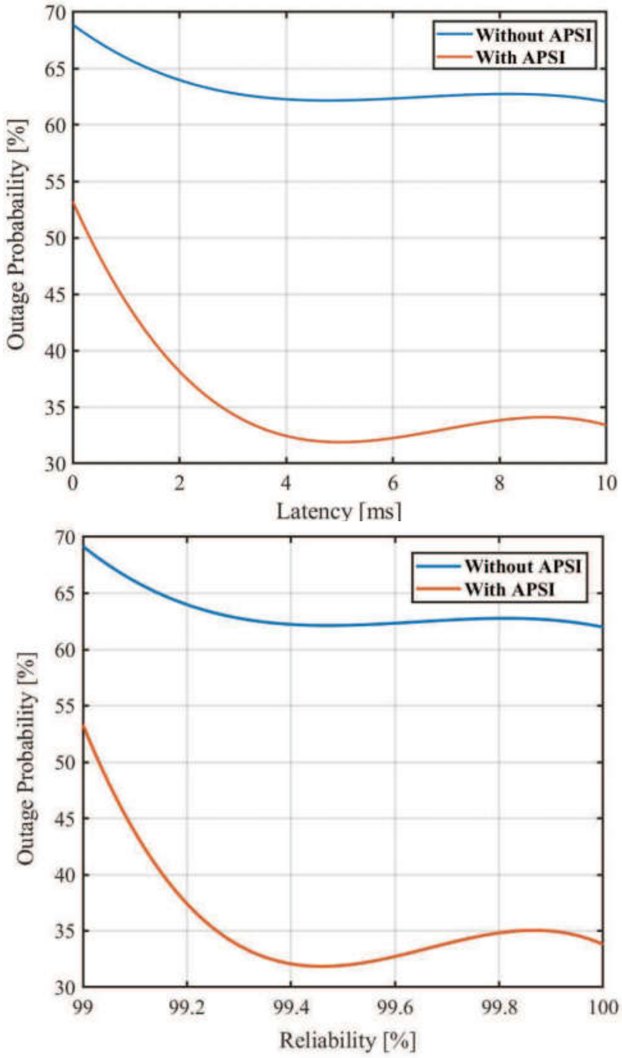

Fig. 4: Outage Probability for number of users with latency and reliability, with or without prior APSI information

A. *Proof for Outage Probability when APSI is unknown*

The random variables X_A and X_B are assumed to have a normal distribution with mean μ and standard deviation σ, since presently no measurement campaigns exist for uRLLC use case cases to obtain statistical distributions. Therefore,

$$X_A, X_B \sim \frac{1}{\sqrt{2\pi\sigma^2}} exp - \frac{(X_{A,B}-\mu)^2}{2\sigma^2}$$

For zero mean and unity standard deviation to achieve simplification, the joint probability distribution in Eq. (1) can be written as

$$P_{out}(\alpha,\beta) = 1 - \int_0^{\alpha_A}\int_{\beta_A}^{\beta_B} \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_A^2}{2}\right) \cdot \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right) dX_A dX_B$$

The limits of latency are taken as $(0, \alpha_A)$ with the lower limit as the ideal value, although it is impossible but near to zero values are expected in tactile internet use cases. The reliability limits (β_A, β_B) are well justified variables to be used in different use case scenarios. From the definition of the error function

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z exp(-t^2)dt, \qquad (5)$$

$P_{out}(\alpha,\beta)$ can be written as

$$P_{out}(\alpha,\beta) = 1 - \int_0^{\alpha_A} \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_A^2}{2}\right) dX_A \cdot \left[\int_0^{\beta_B} \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right) - \int_0^{\beta_A} \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right)\right] dX_B$$

From Eq. (5), $P_{out}(\alpha,\beta)$ can be written in the form of an error function as Eq. (2) with substituting

$$\int_0^z \frac{1}{\sqrt{2\pi}} exp\left(\frac{-x^2}{2}\right) dx = \frac{1}{2} erf\left(\frac{z}{\sqrt{2}}\right)$$

Further, for obtaining Eq. (4), Eq. (3) has to be taken into account. Here, we assume a uniform distribution for APSI, since probability to allocate the index based on reliability and latency of different use cases is considered to be the same. This implies that probability of γ is defined as,

$$P(\gamma) \sim \begin{cases} 0 & for \quad \gamma < c \\ \frac{1}{b-a} & for \quad c \leq \gamma \leq d \\ 0 & for \quad \gamma > d \end{cases}$$

B. *Proof of Outage Probability with known APSI*

First obtaining the conditional probability that latency is less than the provided threshold with available index, in Eq. (3) as,

$$P(X_{A|\gamma=y} < \alpha) = \frac{P_{X_A,\gamma}(\alpha_A, y)}{P_Y(y)}$$

where $P_{X_A,\gamma}(\alpha_A, y)$ is the joint distribution of X_A and γ and $P_Y(y)$ is the marginal distribution of X_A.

$$\Rightarrow P(X_{A|\gamma=y} < \alpha) = \frac{\int_c^d \int_0^{\alpha_A} \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_A^2}{2}\right) \frac{1}{b-a} dX_A d\gamma}{\int_c^d \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_A^2}{2}\right) \frac{1}{b-a} d\gamma}$$

$$\therefore P(X_{A|\gamma=y} < \alpha) = \frac{\frac{\pi}{\sqrt{2}} erf\left(\frac{\alpha_A}{\sqrt{2}}\right)}{exp\left(\frac{-X_A^2}{2}\right)}$$

Similarly, the conditional probability for reliability is obtained as follows:

$$P(X_{B|\gamma=y} > \beta) = \frac{P_{X_B,\gamma}(\beta_A, \beta_B, y)}{P_Y(y)}$$

where, $P_{X_B,\gamma}(\beta_A, \beta_B, y)$ is the joint probability distribution of X_B and γ and $P_Y(y)$ is the marginal distribution of X_A.

Therefore, $P(X_{B|\gamma=y} > \beta)$ is given as

$$\frac{\int_c^d \frac{1}{b-a} d\gamma \int_0^{\beta_B} \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right) - \int_0^{\beta_A} \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right) dX_B}{\int_c^d \frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right) \frac{1}{b-a} d\gamma}$$

$$\Rightarrow P(X_{B|\gamma=y} > \beta) = \frac{\frac{1}{2} erf\left(\frac{\beta_B}{\sqrt{2}}\right) - \frac{1}{2} erf\left(\frac{\beta_A}{\sqrt{2}}\right)}{\frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right)}$$

After obtaining the conditional probability of (X_A, γ) and (X_B, γ), a joint distribution needs to be calculated as given in Eq. (3). Therefore, $P(X_{A|\gamma=y} < \alpha, X_{B|\gamma=y} > \beta)$ is given as

$$P\left[\frac{\frac{\pi}{\sqrt{2}} erf\left(\frac{\alpha_A}{\sqrt{2}}\right)}{exp\left(\frac{-X_A^2}{2}\right)}, \frac{\frac{1}{2} erf\left(\frac{\beta_B}{\sqrt{2}}\right) - \frac{1}{2} erf\left(\frac{\beta_A}{\sqrt{2}}\right)}{\frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right)}\right]$$

$$\Rightarrow$$

$$\int_0^{\alpha_A} \int_{\beta_A}^{\beta_B} \frac{\frac{\pi}{\sqrt{2}} erf\left(\frac{\alpha_A}{\sqrt{2}}\right)}{exp\left(\frac{-X_A^2}{2}\right)} dX_A \frac{\frac{1}{2} erf\left(\frac{\beta_B}{\sqrt{2}}\right) - \frac{1}{2} erf\left(\frac{\beta_A}{\sqrt{2}}\right)}{\frac{1}{\sqrt{2\pi}} exp\left(\frac{-X_B^2}{2}\right)} dX_B$$

Substituting the solution of above integration, in Eq. (3), Eq. (4) is obtained.

V. CONCLUSIONS

In this paper, we studied the problem of latency reduction and reliability enhancements for ultra-reliable low latency communication via a dynamic radio frame configuration through prior antenna port selection index (APSI) information provided to the base station via uplink control channel. APSI information was calculated using a fuzzy logic approach with assumed membership functions. Here, latency and reliability were modeled statistically and closed-form expressions were obtained for outage probability with and without prior available APSI for varying number of users. Proofs and simulation results were provided for the analytical expressions. In future works, the membership functions will be obtained using training data, with neuro-fuzzy systems.

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