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IMPROVING LINK CONTROL FOR ENHANCING QUALITY OF SERVICE IN DATA NETWORKS USING KALMAN FILTER BASED WINDOW FLOW TECHNIQUE

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ABSTRACT

The rapid proliferation of the internet and the heterogeneity of user equipment have led to complex challenges in managing network traffic and ensuring consistent quality of service. Researchers have addressed this issue through the introduction of sliding window link control mechanisms. The sliding window used by the existing ARQ has a fixed window size, as such does not adapt the window size to the dynamic network condition. This study focuses on enhancing network data link control to ensure reliable data transfer, given the increasing diversity in network applications and user base. The proposed approach utilizes a Kalman filter-based sliding window flow control scheme to improve link control in data link networks. Kalman filter estimation and prediction techniques are employed to compute link state statistics in Long Term Evolution (LTE) radio access networks, specifically focusing on Radio Link Control (RLC) acknowledgment request queuing (ARQ) traffic between RLC entities. The algorithm dynamically adjusts the window size based on Kalman filter estimates to optimize sliding window flow control. Results from the evaluation revealed significant improvements of 1.75% in spectral efficiency, 28.81% bit error rate reduction, 16% block error rate reduction, and 36.4% throughput improvement using the sliding window performance as the base line. The study's findings demonstrate the effectiveness of the proposed link control scheme in selecting efficient modulation and coding schemes for data transmission. In conclusion, the research contributes valuable insights to address the challenges posed by the evolving nature of network traffic and user requirements, paving the way for more robust and efficient data link control in modern data networks.

Keywords: Link Control, Sliding window, Spectral efficiency and Kalman filter

1. INTRODUCTION

With the proliferation of the use of smart phones, tablets, laptop computers, Point of Sales (POS) devices, Automated Teller Machines (ATMS) etc. in cellular networks, development of algorithms to improve link control to ensure efficiency and quality of service (QoS) would be an important area of research. Link Control also called Data Link Control (DLC) or Radio Link Control in some wireless Radio Access Technologies like Long Term Evolution (LTE) is the service provided by the Data Link layer of function defined in the Open Systems Interconnection OSI model for network communication (Alluri et. al., 2012). The Data Link layer is responsible for providing reliable data transfer across one physical link (or telecommunications path) within the network. Telecommunication systems are developed to transmit messages from a sender to a receiver. Besides the task of sending and receiving information over a channel, there are many other tasks a communication system has to do. One important task is to guarantee the correctness of the received information. No existing channel is completely error-free. In order to receive correct information, redundancy is often sent. On the receiver side the redundancy is needed to correct errors which have occurred during transmission. Data link layer receives data from next higher layer, adds some control bits i.e. frames are formed at this layer and is handed over to the physical layer. Data link layer removes the control bits and checks for errors. If there is no error, it hands over the received data to the physical layer. The specified set of rules and procedures for carrying out data link control functions is called Data Link protocol. Data-Link layer ensures that an initial connection has been set up, divides output data into data frames, and handles the acknowledgments from a receiver that the data arrived successfully. It also ensures that incoming data has been received successfully by analyzing bit patterns at special places in the frames (Jain, 2013). The process of ensuring that a fast sender does not overwhelm the receiver is known as data link control. The most important responsibilities of the data link layer are flow control and error control. Flow control coordinates the amount of data that can be sent before receiving an acknowledgment and is one of the most important duties of the data link layer. Flow control does not come without a "cost". In a network without flow control, the goodput will rise to a certain point and then drop-off to zero as the offered load increases. Without robust flow control, sessions are more likely to experience delays and even terminating when their retry limits are exceeded. Having sessions terminate is not desirable from a user's viewpoint (Kleinrock, 2016). This impacts strongly on the quality of service (QoS) as seen by the user. Link control is very much associated with congestion control. Congestion control is an endless area of research. Jain et al., (2015) talked about the importance of the available bandwidth in congestion control. Classical and modern control theories have been applied to link control in computer networks. (Mascolo, 2001). In this study a Kalman filter based sliding window flow control is proposed for link control.

2. THEORY OF RESEARCH

2.1 Sliding Window Protocol: The sliding window protocol is a fundamental concept in data communications, and it forms the basis of many link quality control mechanisms. In this method, both the sender and receiver maintain a window of allowable sequence numbers for data packets. The sender can only transmit data within the range of the window, while the receiver acknowledges the receipt of packets and dynamically adjusts the window size based on the received acknowledgments (Gerla and Kleinrock, 1980). In addition, the sliding window protocol can be adapted to monitor and optimize data transmission performance in wireless network. By analyzing the rate of acknowledgment messages received from the receiver, the sender can infer the link quality. If the sender receives acknowledgments for all transmitted packets within a specific window period, it indicates a good link quality, and the sender may increase the window size to enhance data throughput (Eng et al., 2017). Conversely, if acknowledgments are missing or delayed, it implies a potential degradation in link quality, and the sender may reduce the window size to mitigate the impact of packet loss.

2.2 Kalman Filter Technique: The Kalman Filter is considered the greatest achievement in estimation theory of the twentieth century, and it remains a unique accomplishment in the history of estimation theory. It is a powerful mathematical tool used for estimation and control in various fields, including engineering and control systems. The Kalman Filter is known for its ability to minimize mean-squared estimation error and quadratic function of estimation error in linear stochastic systems. The filter uses feedback control to estimate a process, making use of time update and measurement update equations to project the current state and error covariance estimates forward in time and obtain a priori estimates for the next time step.Kalman Filter has been applied in various applications, such as estimating the state of dynamic systems and evaluating the performance criteria of estimation systems. It is especially useful for statistical analysis and predictive design of sensor systems. The proposed technique aims to achieve adaptive adjustment of window size in sliding window flow control, addressing the variability in network conditions. To achieve this, the Kalman Filter is employed as a state estimator to effectively estimate the changing states of the network based on statistical information. The Kalman Filter allows for efficient estimation and prognosis of network conditions, making it a suitable tool for adaptive flow control in dynamic systems.

3. MATERIALS AND METHOD

Materials used include access network traffic data trace obtained from the MTN operated support system (OSS). The trace data used is for the LTE network access link data (down link) network. For all these specifics, a sample of 100 entries is used in the characterization. The modeling and simulation software used is MATLAB/SIMULINK 2018 version. Also a Laptop computer system of with configuration: i7Core, 3.5GH processor, 8GB of RAM and TB of hard disk capacity.

3.1 Modeling Kalman filter algorithm for link control. The key strategy used in the Kalman filter algorithm for link control is the use of Kalman filter estimates and prediction of the state of the link between the RLC entities(at the UE and the eNodeB) to carry out link adaptation for selecting the MCS at the eNodeB. With the predictive capability of Kalman filter, the RLC entity at the eNodeB can quickly adapt the MCS to changes in data link conditions, and improve the transmission efficiency. Usually link control based on the RLC ARQ protocol entails estimating the channel state information by monitoring the contiguous positive ARQ acknowledgment (ACK) or negative acknowledgement (NAK) messages. Based on this monitoring accurate estimate of the link state is very important. To avoid link delays which lead to congestions, drop packets (especially relating to expiry of RLC ARQ poll timers), retransmissions and other error control and flow control issues, accurate and timely estimates of link state statistics is very vital. A delayed and or inaccurate estimate affects the link adaptation at the eNodeB RLC entity. Slow estimates not only delays responses but also results in the use of outdated link state statistics. The reason for this is that, due to slow estimations, by the time the RLC entity at the eNodeB is ready to use the link state estimates it would have been outdated (considering the fast time variations of network traffic). Hence the problem of outdated estimates will be addressed with Kalman predictions. The issue of inaccurate link state estimates from the ARQ traffic can be addresses with the robust estimation capability of Kalman filter. The architecture of the Kalman filter solution is shown in the block diagram of figure 1.

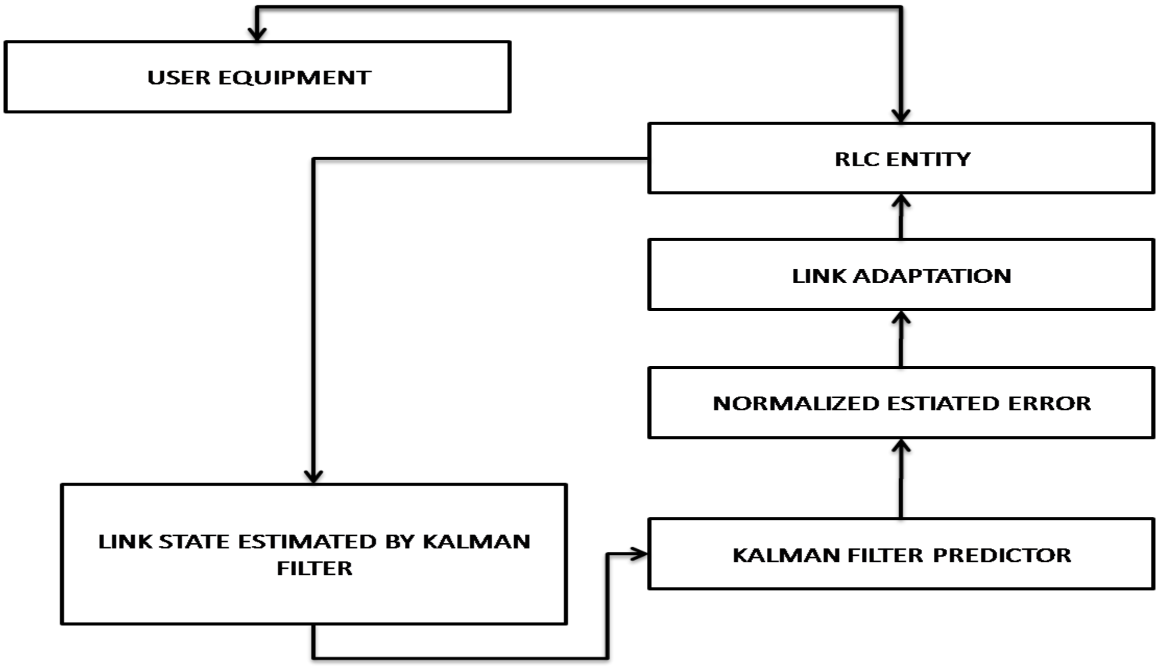

Figure 1: Components of the Kalman filter based link control

Referring to the block diagram of figure 1, the UE computes the SINR on the receipt of a reference signal from the eNodeB and sends the computed SINR as channel (link) state information to the RLC entity at the eNodeB. This measurement of link state is sent by the RLC entity to the Kalman Filter link state estimator. The Kalman filter estimator estimates the data link state statistics base on an autoregressive model of the channel. The estimated link state statistics is sent to the Kalman filter predictor. The Kalman filter predictor uses the estimate of the link state to predict the link state base on a prediction horizon. The Normalized Mean Square Error (NMSE) estimator estimates the prediction error. This is to ensure that the optimal prediction is used for link adaptation. The NMSE purpose is to provide second order statistics of the prediction error. The NMSE function is to ensure that poor predictions are discarded whereas optimal predictions are used for link adaptation. The adaptation uses the link state to choose the most optimal MCS.

3.2 Model for obtaining the link statistics. The input to the Kalman filter is a measurement or estimate of the radio network link at time k. In the Kalman filter based approach, the state of the system is estimated from repeated measurements of the CQI in the case of the modeling carried out in this work (or some quantity in other use case). The measured quantity (in this case CQI) is dependent on the system state. To use the Kalman filter, requires models of how the system state evolves from one measurement occasion to the next, and also how the measured quantity depends on the system state. The system equations can be expressed as;

$$x_k = Ax_{k-1} + w_{k-1} \qquad (1)$$

$$z_k = H_h x_k + v_k \qquad (2)$$

Where x is the state of the system (in this case the data link), z is the measured quantity between the UE and the eNodeB), w is the process noise and v is the measurement noise. The vector z includes the radio link between UE and eNodeB.From the previous estimate and the new measurement, the Kalman filter equations allow estimation of the system state x and the error covariance matrix Pas

$$\hat{x}_k = \hat{x}_k^- + K_k \gamma_k \qquad (3)$$

$$P_k = (1 - K_k H_k)P_k^- \quad (4)$$

Where

$$\hat{x}_k^- = A\hat{x}_{k-1}^- \quad (5)$$

$$P_k^- = AP_{k-1}A^T + Q \quad (6)$$

and

$$K_k = P_k^- H_k^T V_k^{-1} \quad (7)$$

$A$and$H$ are state matrices; Q is process-noise covariance; K_k is the Kalman gain ;γ_k is known as the residual or innovation. It is essential in the Kalman filter correction phase.The residual reflects the deviation of the actual measurement from what is predicted according to the measurement model and the evolved state estimate. The Kalman filter procedure takes a previous estimate $\hat{x}_{k-1}$ and a new measurement $z_k$as input, and calculates a new estimate $\hat{x}_k$of the system state. The Kalman filtering can be understood as an iterative process where each step consists of two phases of calculation. First, there is a prediction phase, where the previous estimate evolves one discrete time step according to the system model. Then, there is a correction phase, where the new measurement is taken into account. The updated error covariance matrix P_k of the state estimate is also computed.

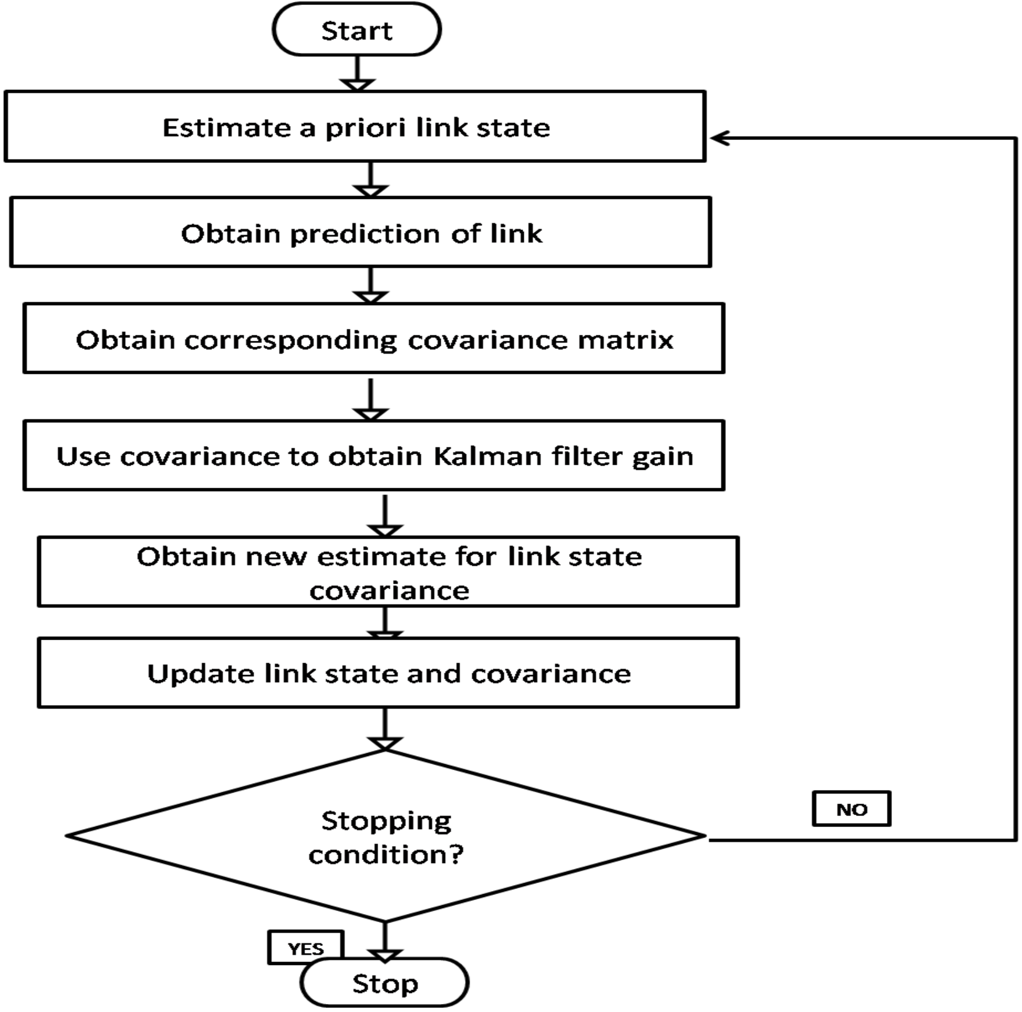

Figure 2: The Kalman filter computational process

3.3 Integrating Kalman filter with sliding window flow for link control. The estimation and prediction capability of Kalman filter is used to create a link control scheme that integrates Kalman filter technique and sliding window flow technique. The strategy is to use Kalman filter computational framework to track the state of the data link (i.e. the process state) in order to extract information used in an optimization scheme for the adaptation of the sliding window size. The Kalman filter computation is used to provide parameters (in this case available bandwidth estimation) used within an optimization process to select window sizes (within the allowable range) that minimizes the back pressure (that is that minimizes the blocking probability). The method used in the integration of Kalman filtering and sliding window flow control involves the use of active probing and Kalman filtering. The block diagram shows the components of the integrated link control scheme.

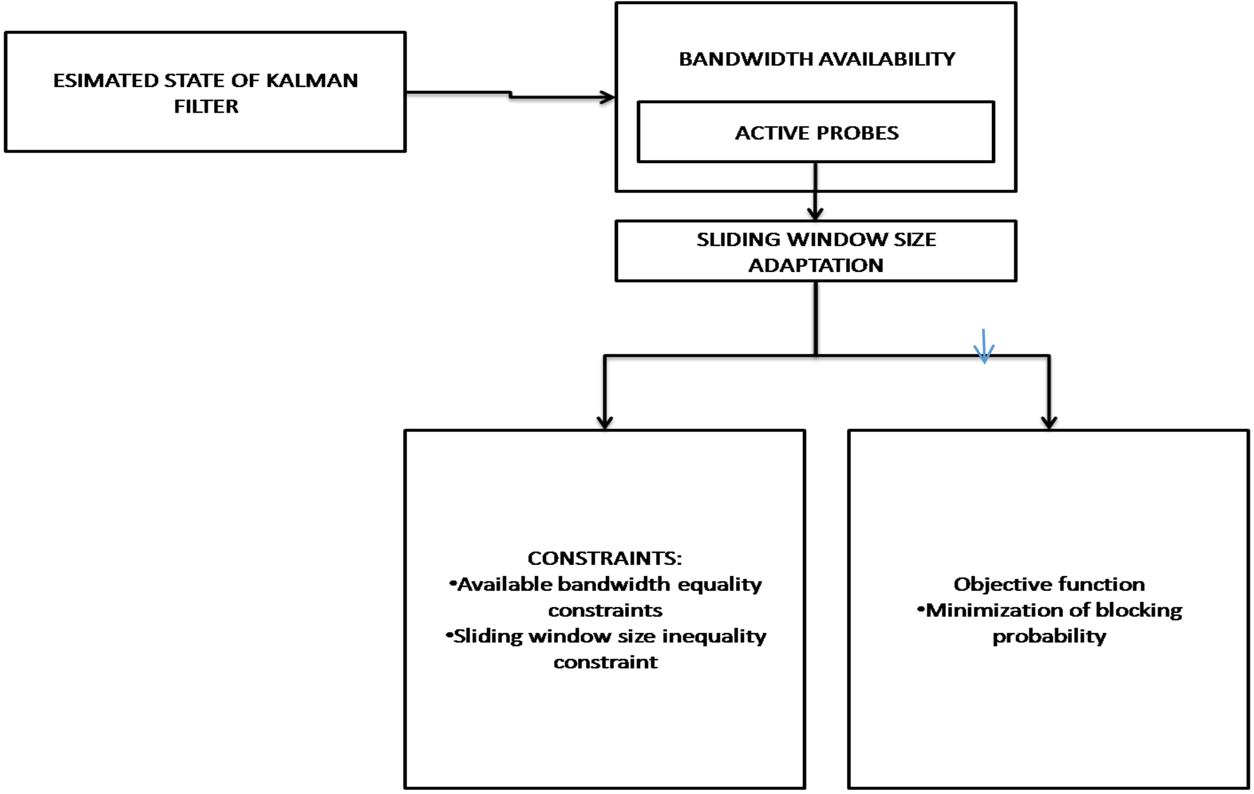

Figure 3 Integrating Kalman filter with Sliding window flow for link control

To improve on the sliding window flow control by adapting the window size, the system state (the link state) has to be tracked. Doing this requires real-time estimation. This is where the Kalman filter computational framework is required. With reference to the block diagram, the Kalman filter component of the system carries out its computational tasks based state estimation and parameter measurements. With regards to the Kalman filter state estimates and measurements, in this integration of Kaman filter with sliding window flow, the updated estimate of the system state is produced based on probe-packet measurement. After the Kalman filter has performed its calculations, the filter output is fed into the available bandwidth estimation process, which updates the available bandwidth estimation based on the values from the Kalman filter. The updated bandwidth is the output of the of the available bandwidth estimation process block. The available bandwidth estimation process block, shown in the diagram, makes use of active probing and Kalman filtering. The active probing method used in this design is the Bandwidth Available in Real–Time (BART) method. This technique uses Kalman filtering for real-time estimation of available bandwidth. Real–time estimate of available bandwidth is used for the adaptation of the sliding window size in an optimization procedure (used as equality constraint in the optimization procedure). Reason for use of the active probe is that estimation of end-to-end available bandwidth is usually accomplished by active probing (citation needed). By injecting probe traffic into the network, and then analyzing how the probes are affected by link capacities and other traffic along the measured network path, the available bandwidth can be estimated. For the update of the Kalman filter state estimate, the inter-packet separation strain of consecutive probe packets is used. In the sliding window size adaptation process, the available bandwidth obtained is used as equality constraint. The objective function for the optimization function is the minimization of the back-pressure (i.e. minimization of the blocking probabilityP_{Bi}). Two constraints are to be met in the selection of the optimal sliding window size: (1) the available bandwidth must be equal (i.e. the equality constraint) to that estimated via BART (2) the possible window size must be greater than zero but less than (i.e. the inequality constraint) the maximum allowable window size as per ARQ. The available bandwidth estimation algorithm used is described as follows:

1. The receiver initializes the state vector estimate $\hat{x}$ as well as the available bandwidth estimate $\hat{B}$and the error covariance matrix P of $\hat{x}$.
2. The sender generates a sequence of probe-packet pairs with probe-traffic intensity$u$, for instance drawn from a selected probability distribution. The value of the probe-packet intensity is carried in each packet.
3. For each received probe sequence, the receiver recovers$u$. If $u \leq \hat{B}$ no updatingis performed and the cycle repeats from step 2. If $u > \hat{B}$ the receiver computes the average strainε, which corresponds to z using the Kalman filter notation (13).
4. The receiver inputs the strain measurement to the Kalman filter, and alsoprovides the filter with an estimate of the process-noise covariance Q andthe measurement-noise covariance R. The filter then updates the estimatesof the state vector $\hat{x}$ and the matrix P.
5. The receiver uses the updated $\hat{x}$ to compute a new u-axis crossing, producinga new available-bandwidth estimate $\hat{B}$.The cycle repeats from step 2.

4. RESULTS AND DISCUSSION

This section presents the performance of the kalman filter based estimation model which was used to optimize the sliding window link controller. The Kalman filter algorithm developed to predict the network behavior considering the available bandwidth model in figure 3 and also the error were used to determine the network state and then used the sliding window to adjust the modulation and coding scheme for improved quality of service update. In a situation where the network information prediction implied poor performance through low bandwidth availability and error high, larger sliding window and link parameters are used to adjust the modulation and coding scheme of the link control. By leveraging a larger sliding window and adjusting link control parameters based on network information predictions by the Kalman filter, the system can optimize its performance by striking a balance between data rate and reliability. This dynamic adaptation allows the wireless network to maintain a usable and stable link, even under adverse conditions, while maximizing throughput when the network quality is good. To evaluate the predicted error on the network, the block error rate and bit error rates respectively were utilized and reported in the figure 4; while throughput and SINR were used to evaluate the predicted bandwidth availability performance and reported in figure 5;

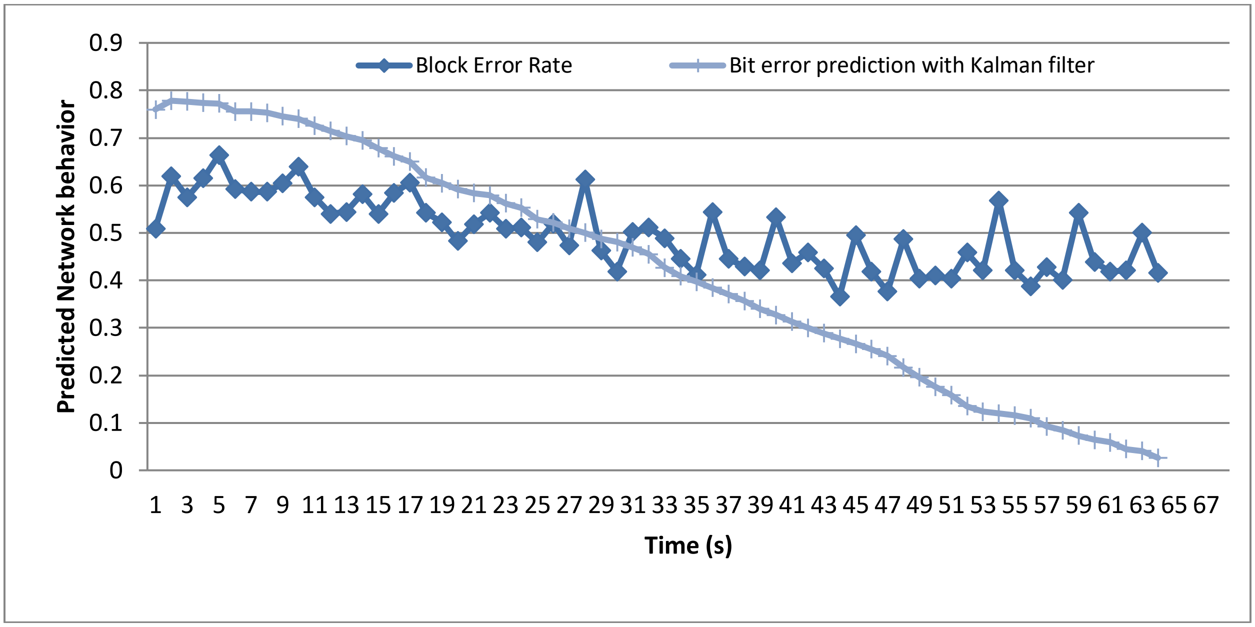

Figure 4: Kalman filter predicted network error

The figure 4 presented the performance of the Kalman filter which was used to predict the error on the network considering the bit error and block error performance. The predicted outcome implies that while the bit error is poor and gradually improves, the block error was inconsistent and fair. The reason for the inconsistency was due to other external network factors such as interference and congestion, which will be further revealed considering the bandwidth availability as analyzed considering throughput in figure 5;

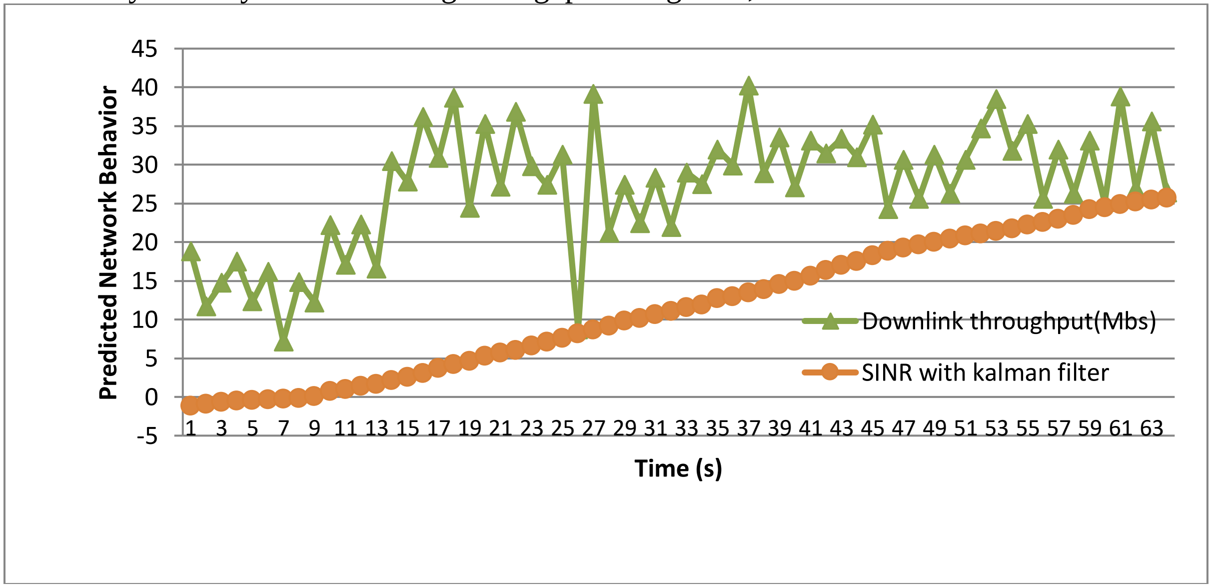

Figure 5: Kalman filter predicted bandwidth availability

The figure 5 presents the bandwidth availability performance considering throughput and SINR. From the result in the graph, it was observed that while the SINR gradually improves, the throughput is nonlinear due to the adjustment of the modulation and coding scheme by the sliding window.

In the next result of figure 6 section presents the performance of the Kalman filter based link control algorithm modeled which was used to optimize the link control of the 4G network through the prediction of the network behavior, enabling real-time adaptability, and optimizing performance. It accurately estimates critical parameters like SINR and BER, etc. allowing the link control algorithm to make informed and adaptive decisions. The filter's real-time tracking capabilities enable quick responses to dynamic network conditions, such as interference and channel variations. By reducing measurement noise, the Kalman filter based link control algorithm provides a more stable and focused relationship between link control metrics, mitigating the scattering effect. To evaluate the kalman filter algorithm through simulation, performance indicators such as spectral efficiency, bit error rate and block error rate. The spectral efficiency of the network with kalman filter was evaluated and the result was reported in the figure 6 for link control estimation;

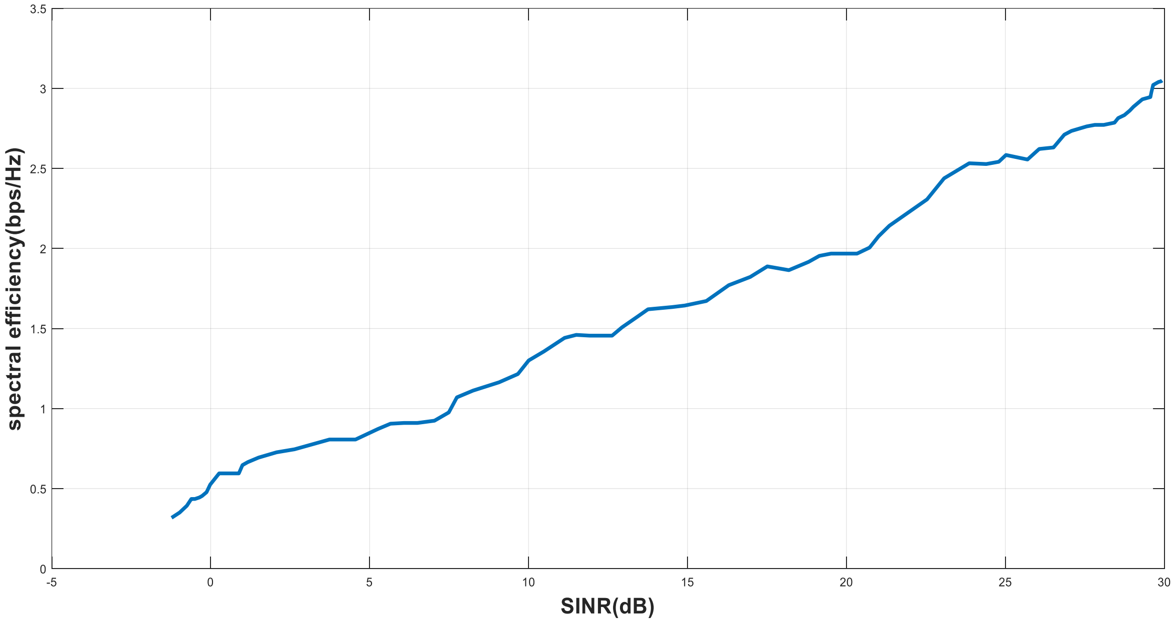

Figure 6: spectral efficiency of the network with Kalman filter

From the figure 6, the relationship between the spectral efficiency and SINR was analyzed, and result showed trajectory of increase SINR resulting to increase spectral efficiency, which is normal, however, considering the standard for best practices, it was observed that the dynamic network condition such as the presents of interference, congestion, etc all impacted on the network performance, and the lack of adaptive reaction to select suitable coding and modulation scheme compatible to the network data a time, reflected on the behavior observed. In other words, the system did not efficiently adjust its coding and modulation methods to suit the specific data requirements at different points in time. Consequently, the network's inability to adapt appropriately to the varying conditions had a direct impact on its overall performance. This lack of adaptability manifested in the observed behavior, leading to diminished spectral efficiency compared to what could have been achieved with more dynamic and responsive coding and modulation schemes. Similarly the bit error was evaluated with the kalman filter based sliding window developed and then reported in the figure 7;

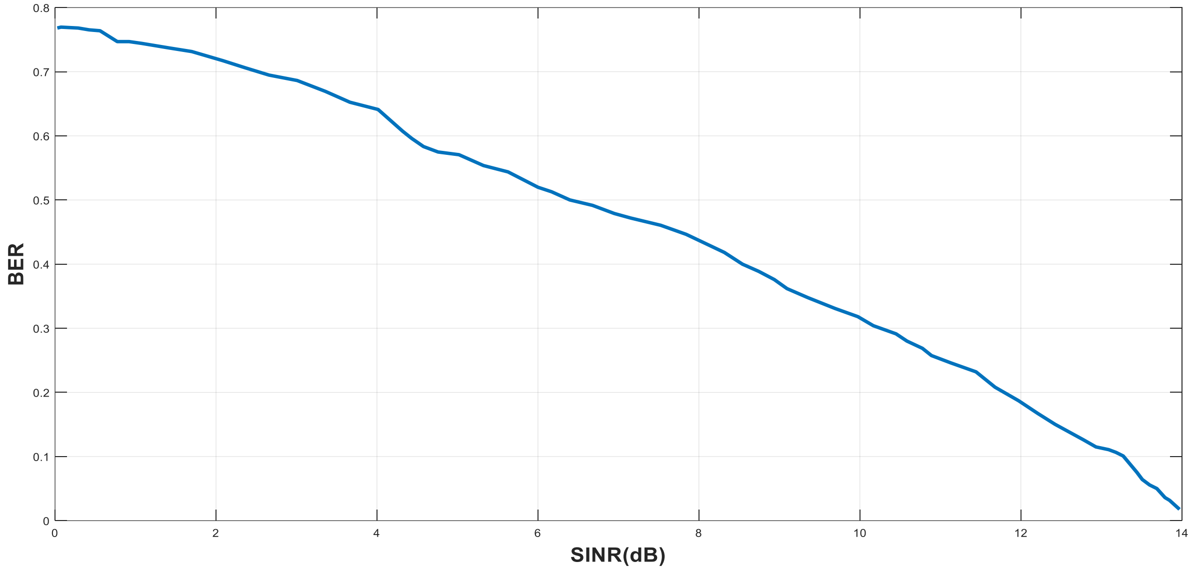

Figure 7: Bit Error Rate of the Kalman filter based window flow link control

The figure 7 presents the BER of the network against SINR with Kalman filter. The result showed that overall the BER is poor as it did not satisfy the requirement of the MTN best practices. In addition, SINR gradually increased with time, as the BER also improves with time, this implying the action of the kalman filter in optimizing the link control through the adjustment of the coding and modulation scheme to suit the network condition. In another result, block error rate and transport block of the network were investigated and analyzed using the figure 8. From the result, the block error rate is 0.42, while the transport block is 448.97.

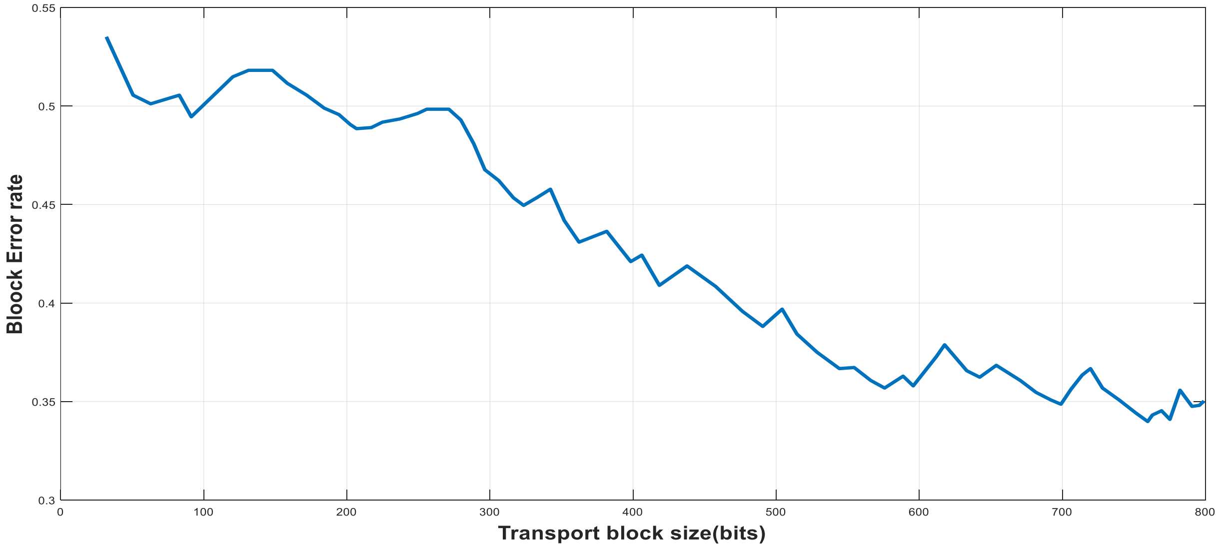

Figure 8: variation of block error rate with transport block size when the proposed Kalman filter based window flow link control algorithm was used.

The figure 8analysis explores the link control results concerning Block Error Rate (BER) and Transport Block Size. It is observed that an increase in Signal-to-Interference-plus-Noise Ratio (SINR) leads to higher spectral efficiency, as expected. However, the scattering effect in the data indicates variations in link performance. To address this, the application of the Kalman filter through parameter estimation by accurately predicting crucial network conditions was used. This adaptability allows the link control algorithm to make more informed decisions, optimize spectral efficiency, and react to dynamic network conditions, such as interference and congestion.

5. CONCLUSION

The combined improvements in throughput, spectral efficiency, and reduction in bit error and block error rate indicate an enhanced quality of network link conditions. These link conditions play a crucial role in determining the modulation and coding scheme used by the system for data transmission between the sender and receiver, thereby influencing the amount of data the system can carry in each resource block. The results obtained from the comparative evaluation in this study demonstrate that the proposed Kalman filter-based Sliding window flow control scheme increases the likelihood that the RLC entities will not opt for more robust modulation and coding schemes. As a result, the proposed link control scheme enhances the capability of RLC entities to select more efficient (less robust) modulation and coding schemes for data transmission across the data link. Furthermore, an effective link control scheme, such as the one proposed in this work, improves throughput and spectral efficiency, leading to a reduction in underutilized resources and increased network link utilization. This improvement in link utilization helps alleviate resource pressure, network congestion, and connection timeouts. In summary, the enhanced link control scheme allows network operators to conserve network resources, reduce energy consumption, minimize operational costs, and lower the cost of data subscriptions for end-users.

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