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KALMAN FILTER BASED SLIDING WINDOW APPROACH FOR OPTIMIZED LINK CONTROL IN 4G WIRELESS NETWORK

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ABSTRACT

This paper presents smart link control scheme for wireless networks based on Kalman filter-sliding window controller. The scheme aims at improving the controller adjustment and the network link quality by selecting the optimal modulation and coding scheme for data transmission. The scheme is designed and implemented using MATLAB and evaluated through simulation. The results show that the new system with smart link control achieves better performance in terms of throughput, spectral efficiency, and bit error rate than the conventional link control schemes. In addition, it reduces the probability of using more robust modulation and coding schemes by the Radio Link Control entities, thus increasing the data rate and the resource utilization of the network.

Keywords: Kalman Filter; Sliding Window; Data Transmission; Radio Link Control

1. INTRODUCTION

Computer networking relies on data link control, a crucial and complex function that ensures reliable and efficient data exchange among interconnected devices using a shared communication medium. Data link control operates as the second layer of the OSI model and has multiple responsibilities, such as managing data flow, detecting and correcting errors, and regulating access to the communication channel (Krieger and Kumar, 2018). Data link control has evolved over time to overcome the challenges of transmitting data with high accuracy and efficiency. One of the main challenges was the lack of effective error detection and correction methods, which resulted in unreliable data transmission (Jain, 2014). To address this issue, data link control developed various strategies and protocols that provided a structured way of data transmission and allowed receivers to recognize the start and end of each data frame (Sastry, 2018). However, data link control still faces some problems that affect the performance and cost of data networks.

One of these problems is the excessive re-transmission of data by mobile devices due to ineffective link control schemes. This problem leads to increased data consumption and cost for end users, as well as higher energy usage and battery drain for mobile devices and network equipment such as switches, routers, and base station transmitters. Another problem caused by poor link control schemes is the disruption of business activities that depend on video and audio streaming over data networks. Poor link control schemes can cause network congestion and delays by exhausting the buffer memories of network switches and routers (Adesh and Renuka, 2019). Moreover, poor link control schemes can affect the link adaptation mechanism in modern Radio Access Technologies (RATs) such as Long Term Evolution (LTE). Poor link control schemes can result in inappropriate selection of Modulation and Coding Scheme (MCS) for data transmission between the UE and the eNodeB, which reduces the amount of data that can be transported in a resource block and lowers the network throughput (Matías et al., 2017). In this paper, we propose to use Kalman Filter to improve the radio link control in data networks. We expect that this method will enhance the performance and efficiency of data transmission and reduce the problems associated with poor link control schemes.

2. DESIGN METHOD

This research work will use both simulation and mathematical modeling methods to develop and test models using MATLAB software. The first step is to design a Kalman filter algorithm for link control in data networks, which can predict the state of the network data link and adjust the sliding window size accordingly. This can overcome the limitations of existing link control techniques that are not adaptive to the network conditions. The Kalman filter algorithm also aims to improve the state estimate accuracy from the ARQ traffic. To obtain the Kalman filter algorithm, the data link state statistics are estimated based on an autoregressive model of the channel. Figure 1 illustrates the Kalman filter architecture and figure 2 demonstrates the Kalman filter computation process. The next major step is to create a MATLAB/SIMULINK model as a platform for implementing, evaluating and validating the proposed link control scheme. The final step is to simulate, present and discuss the results. The main objective here is to verify whether the simulation results indicate that the proposed scheme can enhance the network performance metrics related to link characteristics such as spectral efficiency, link utilization and throughput

2.1 **Laboratory/Field Work/Simulation**

To evaluate the current link control scheme, simulation is needed to generate and assess the link traffic of the LTE access network layer using field data. A MATLAB/SIMULINK model of the existing LTE Radio Link Control (RLC) was applied for this purpose. A link traffic trace dataset containing link metrics such as reference signal received quality (RSRQ), SINR and Channel Quality Information (CQI) was obtained from MTN as part of field work. This dataset was derived from network instrumentation servers that collect link state traffic data from base eNodeBs.

2.2**Data Collection**

The data on the LTE radio network access was collected from MTN Nigeria, the network provider. The network trace dataset includes UE measurements of the radio link states, RLC operational parameters and link adaptation, and variables from the network operator's Operation Support System (OSS). This dataset covers transmission data for eNodeB's and UE components in the air interface. The data for the eNodeB's located at the coordinates (6^{o}26 `25 ‟N $7^{o}$30 `13 ‟ E) in the Enugu metropolis was used to evaluate the performance of the link control scheme implemented. The data was for the downlink transmission. The eNodeB was connected to antenna sections that spanned an arc of 120° each. Table 1 shows the transmission trace data-set from the live case study network. The network data trace data-set contains radio link strength values such as signal strength, Reference Signal Received Power (RSRP), and Reference Signal Received Quality (RSRQ). These indicators reveal the channel quality between the RLC entities, i.e., the eNodeB and UE. The trace data-set from the live LTE network of the MTN network operator shows the radio link condition between the eNodeB and the UE. The radio link signal strength values are measurement reports from the RLC entities, which reflect the effect of link adaptation process on the radio link performance. The resource block (RB) usage rate and the base station load of the case study network have to be calculated from the trace data-set. The collected data was reported in Appendix A.

3. MODELLING KALMAN FILTER ALGORITHM FOR LINK CONTROL

The main idea of the Kalman filter algorithm for link control is to use Kalman filter estimates and prediction of the link state between the RLC entities (at the UE and the eNodeB) to perform link adaptation and choose the MCS at the eNodeB. The RLC entity at the eNodeB can rapidly adjust the MCS to the changes in data link conditions, and enhance the transmission efficiency, thanks to the predictive ability of Kalman filter. Link control based on the RLC ARQ protocol requires estimating the channel state information by observing the consecutive positive ARQ Acknowledgment (ACK) or negative acknowledgement (NAK) messages. This observation is crucial for accurate estimate of the link state. To prevent link delays that cause congestions, drop packets (especially those related to expiry of RLC ARQ poll timers), retransmissions and other error control and flow control problems, precise and prompt estimates of link state statistics are essential. Delayed or inaccurate estimates affect the link adaptation at the eNodeB RLC entity. Slow estimates not only postpone responses but also lead to the use of obsolete link state statistics. This is because, due to slow estimations, the link state estimates would have become outdated (considering the fast time variations of network traffic) by the time the RLC entity at the eNodeB is ready to use them. Therefore, Kalman predictions will solve the problem of outdated estimates. The issue of inaccurate link state estimates from the ARQ traffic can be solved with the robust estimation ability of Kalman filter.

The architecture of the Kalman filter solution is shown in the block diagram of figure 1.

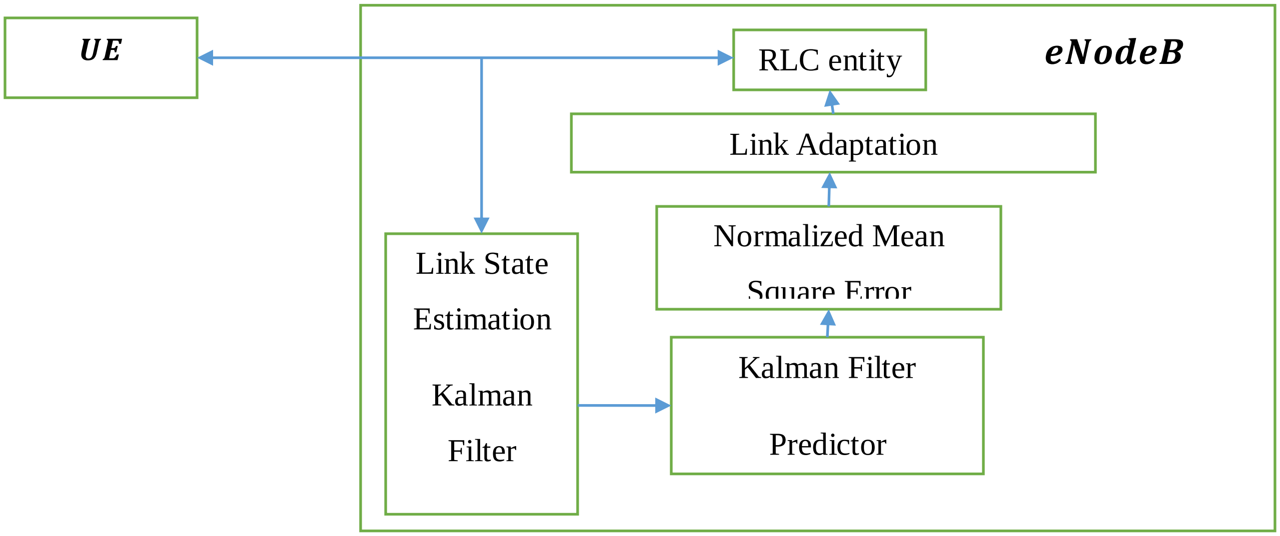


Figure 1: Components of the Kalman filter based link control

Figure 1: Components of the Kalman filter based link control As shown in the block diagram of Figure 1, the UE calculates the SINR after receiving a reference signal from the eNodeB and sends the SINR as channel (link) state information to the RLC entity at the eNodeB. The RLC entity forwards this link state measurement to the Kalman Filter link state estimator. The Kalman filter estimator determines the data link state statistics using an autoregressive model of the channel. The Kalman filter predictor receives the estimated link state statistics and predicts the link state based on a prediction horizon. The Normalized Mean Square Error (NMSE) estimator evaluates the prediction error. This ensures that the link adaptation uses the optimal prediction. The NMSE provides second order statistics of the prediction error. The NMSE discards poor predictions and selects optimal predictions for link adaptation. The adaptation chooses the most optimal MCS based on the link state.

3.1 **Model for Obtaining the link statistics**

The Kalman filter uses a measurement or an estimate of the radio network link at time to estimate the system state from repeated CQI measurements. The Kalman filter needs models of how the system state changes from one measurement to another, and how the system state affects the measured quantity. The system equations are:

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

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

Here, *x* is the system state (the data link in this case), *z* is the measured quantity between the UE and the eNodeB, *w* is the process noise and *v* is the measurement noise. The vector zcontains the radio link between UE and eNodeB. The Kalman filter equations estimate the system state *x* and the error covariance matrix *P* from the previous estimate and the new measurement as follows:

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

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

Where

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

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

And

$$K_k = P_k^- H_k^T V_k^{-1} \tag{7}$$

$A$and $H$are state matrices; $Q$is process-noise covariance; $K_k$is the Kalman gain; $\gamma_k$is the residual or innovation, which is important for the Kalman filter correction phase. The residual shows the difference between the actual measurement and the predicted measurement based on the measurement model and the updated state estimate. The Kalman filter process 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 is an iterative process with two steps of calculation. First, there is a prediction step, where the previous estimate changes one discrete time step according to the system model (5). Then, there is a correction step, where the new measurement is considered (3). The error covariance matrix $P_k$of the state estimate (4) is also updated.

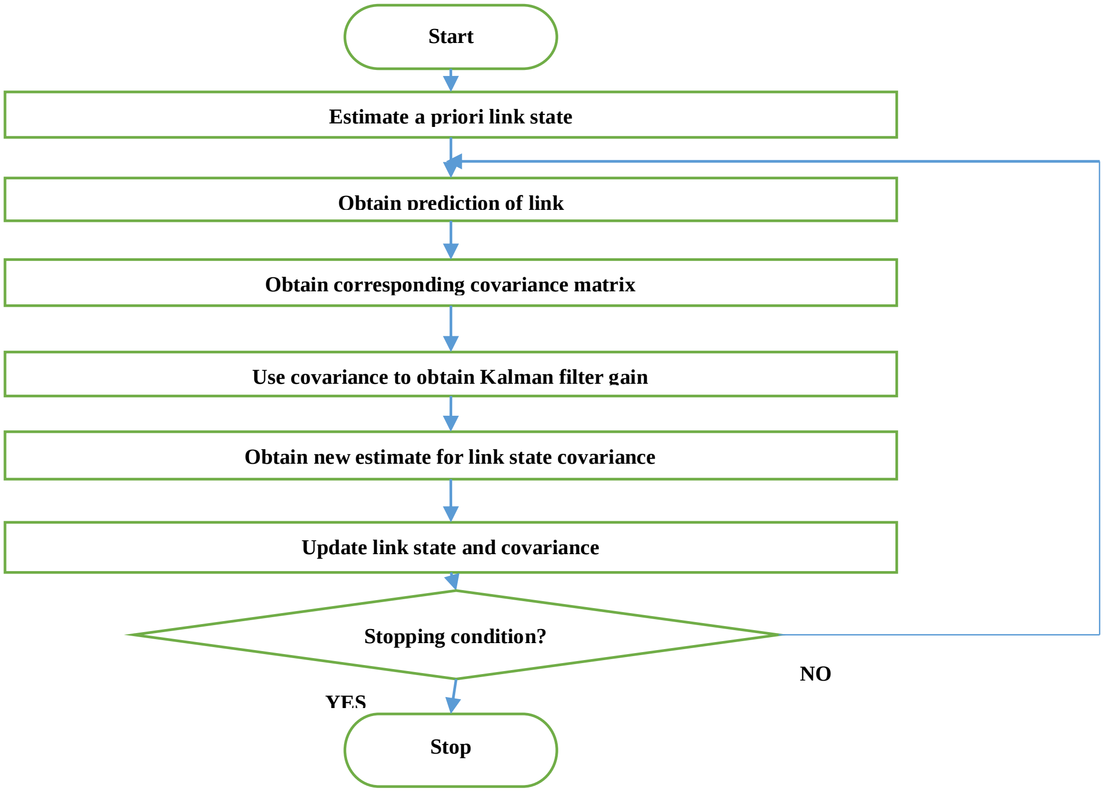


Figure 2: The Kalman filter computational process

3.2 **Integrating Kalman filter with sliding window flow for link control.**

The sliding window protocol is a key idea in data communication, and it underlies many link quality control methods. This technique involves both the sender and receiver keeping a window of valid sequence numbers for data packets. The sender can only send data within the window, while the receiver confirms the packets and changes the window size based on the confirmations (Gerla and Kleinrock, 1980). The Kalman filter can estimate and predict the data link state (the process state) and use this information for an optimization scheme that adapts the sliding window size. The integration of Kalman filtering and sliding window flow control uses active probing and Kalman filtering. The block diagram illustrates the integrated link control scheme components. The block diagram shows the components of the integrated link control scheme.

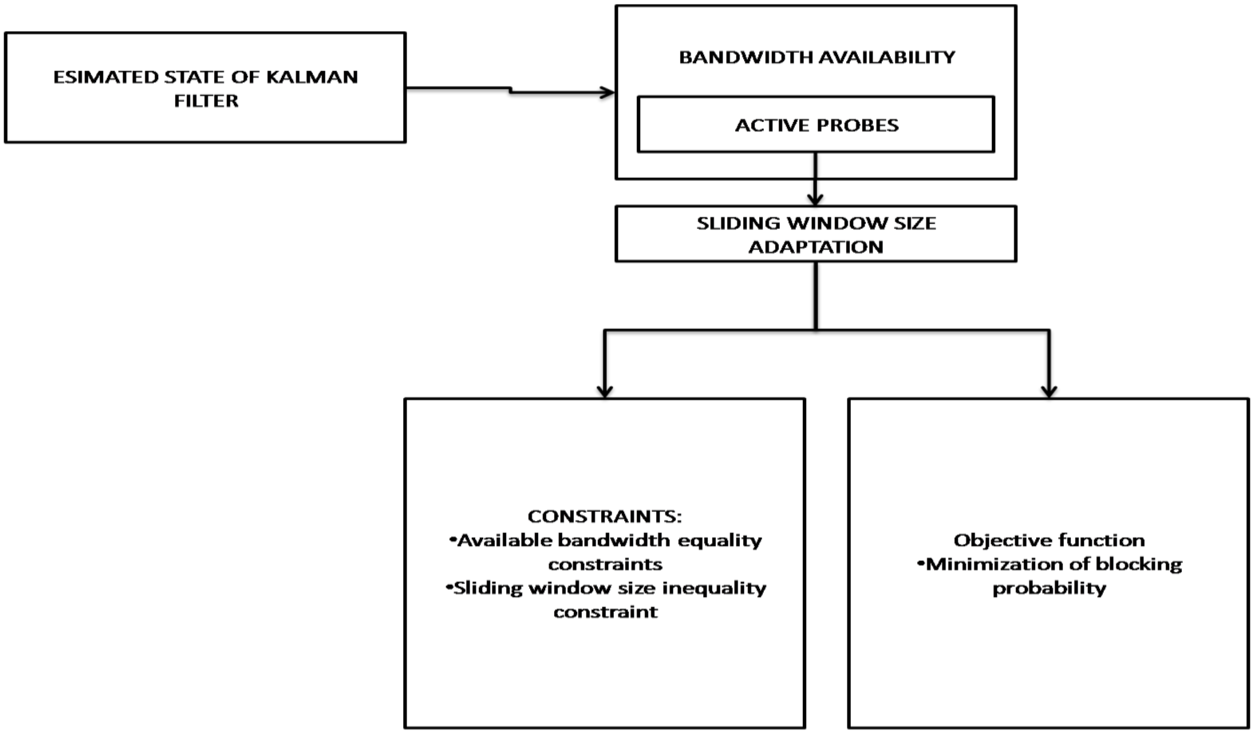


Figure 3: Integrating Kalman filter with Sliding window flow for link control

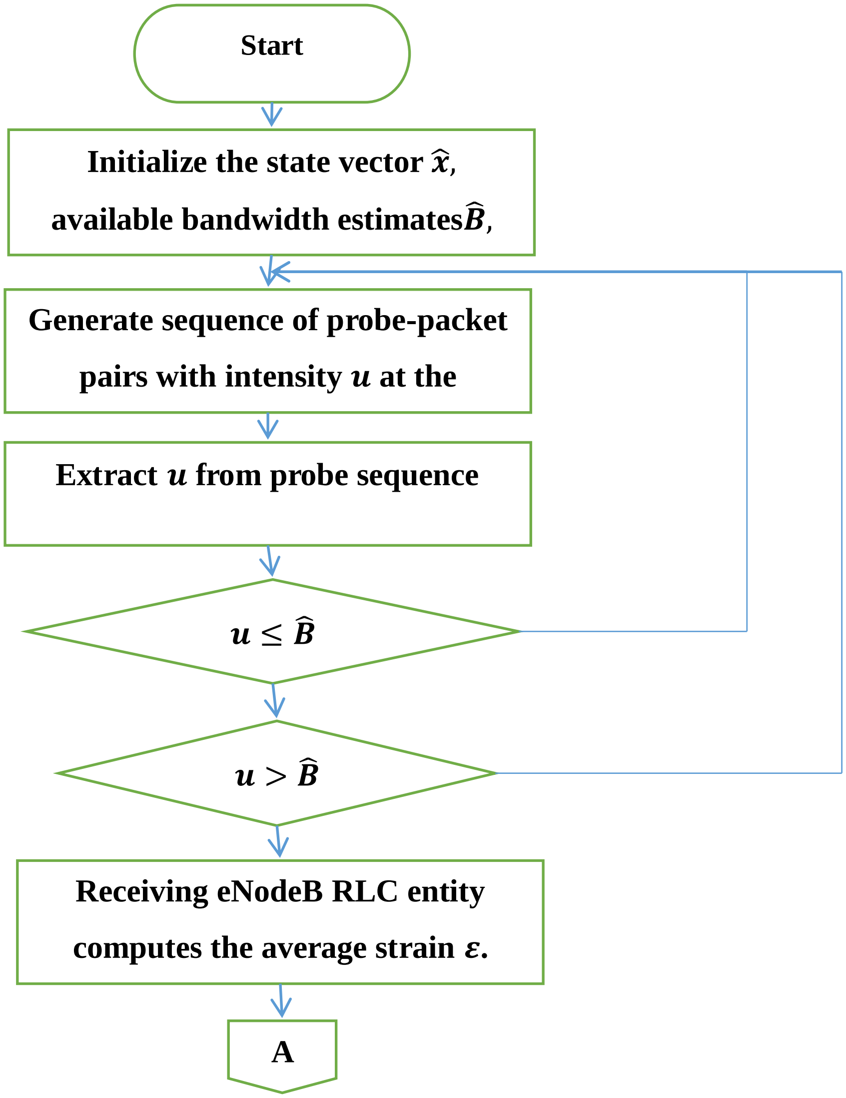
To improve on the sliding window flow control by adapting the window size, the system state (the link state) has to be tracked. Doing this requires real-time estimation. This is where the Kalman filter computational framework is required.

The available bandwidth estimation algorithm used in the system 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.
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 strain ε, which corresponds to z using the Kalman filter notation.
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.

Figure 4 shows the flow chart of the computation procedure for the Available bandwidth estimation.



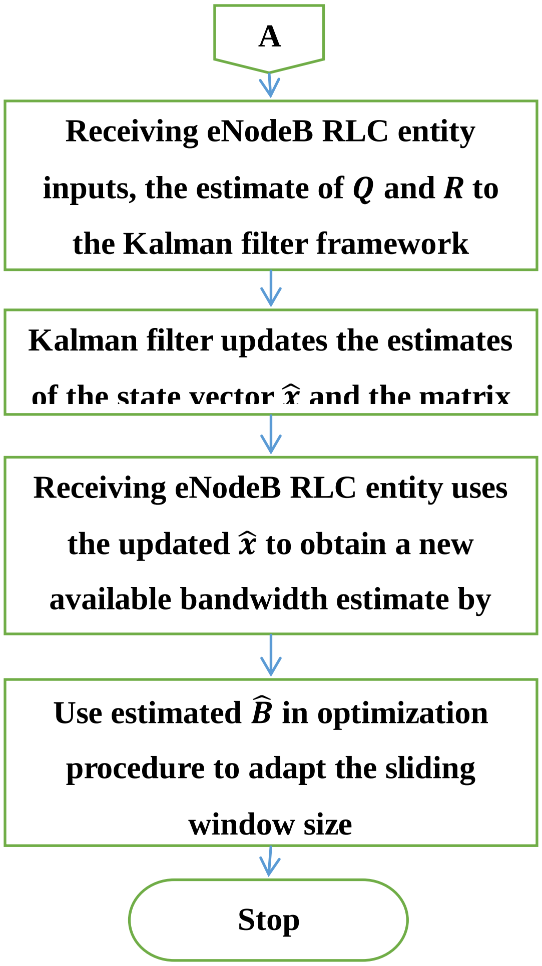


Figure 4: Flow chart of the computation procedure for the Available bandwidth estimation.

The relation of the measurement of inter-packet strain as a function of probe-traffic intensity is given as a piece-wise function. The expectation value of ε is zero when the probing intensity u is less than the available bandwidth B, and grows in proportion to the overload when the probing intensity is larger:

$$\varepsilon = \begin{cases} 0 & (u \leq B \\ \alpha(u - B) = \alpha u + \beta & (u > B) \end{cases} \qquad (8)$$

The model represented by equation (8) shows that the piece-wise function representing ε is made up of two lines segments i.e.$\varepsilon = 0$and $= \alpha u + \beta$, where the parameters α and β are the gradient and intercept of the line segment. These parameters have to be determined via Kalman filtering.Since the measurement model represented by (8) is piece-wise linear, the break point at $u = B$ prevents a direct application of a Kalman filter. In order to circumvent this, the filter is only applied to measurements for which $B > \hat{B}$where $\hat{B}$ is the current estimate of the available bandwidth, which is known.

4. SIMULATION MODEL OF THE LTE NETWORK EXPERIMENTAL TEST BED

The test bed for the proposed link control concept requires an LTE network model. The MATLAB LTE toolbox provides code libraries for the core LTE network functionalities. The simulator development uses an Embedded MATLAB function for the Pre-coding Matrix Indicator (PMI) calculation. The LTE test bed simulator uses the Rectangular Quadrature Amplitude Modulation (QAM) Demodulator Base-band block from the Simulink library for the demodulator. The LTE simulator implements the segmentation, zero-padding and soft combining functions with an Embedded MATLAB Function block. The link control algorithms need to be implemented in software for the simulation. The Kalman Filter algorithms are coded in MATLAB M-file codes. These software systems are integrated with the Simulation model of the LTE network experimental test bed. The simulation program runs the traffic generation code module with the traffic model obtained from the link characteristics model (Kozo et.al., 2020) to generate the characteristic network traffic. The next section presents and discusses the simulation results.

5. RESULTS AND DISCUSSION

This section shows the results of the Kalman filter based estimation model that optimized the sliding window link controller. The Kalman filter algorithm predicted the network behaviour based on the available bandwidth model in figure 4 and the error in equation 8. These predictions determined the network state and adjusted the modulation and coding scheme with the sliding window for better quality of service. When the network information prediction indicated low bandwidth availability and high error, the link control used larger sliding window and link parameters to adjust the modulation and coding scheme. This dynamic adjustment enabled the wireless network to keep a reliable and stable link, even in bad conditions, and increase throughput when the network quality was good. The block error rate and bit error rates measured the predicted error on the network and were shown in figure 5. The throughput and SINR measured the predicted bandwidth availability performance and were also shown in figure 5.

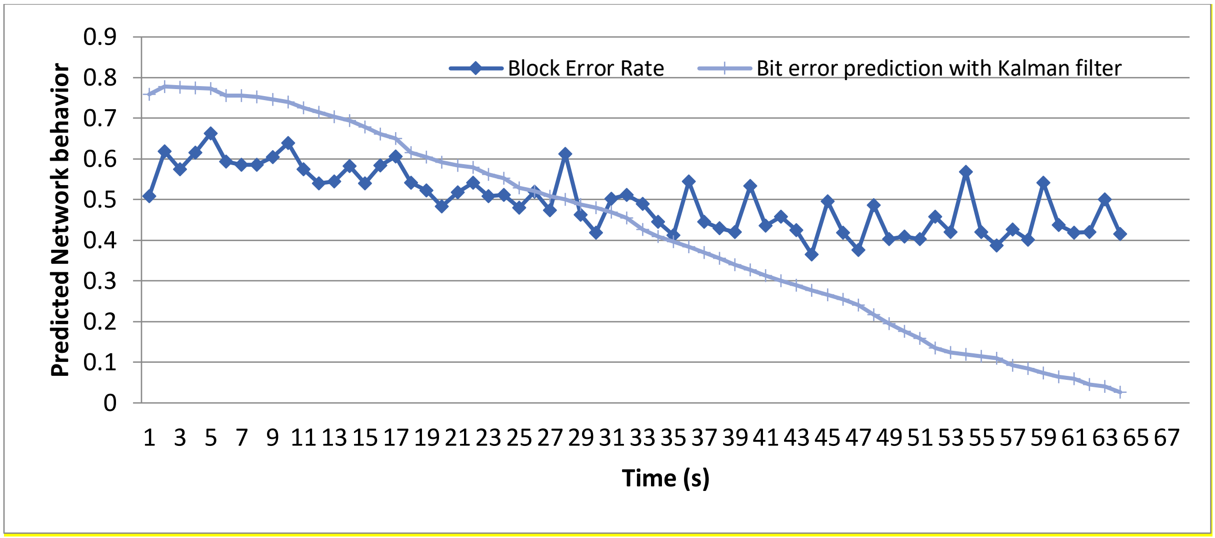


Figure 5: Kalman filter predicted network error

The figure 5 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 when analysed 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 analysed considering throughput in figure 6;

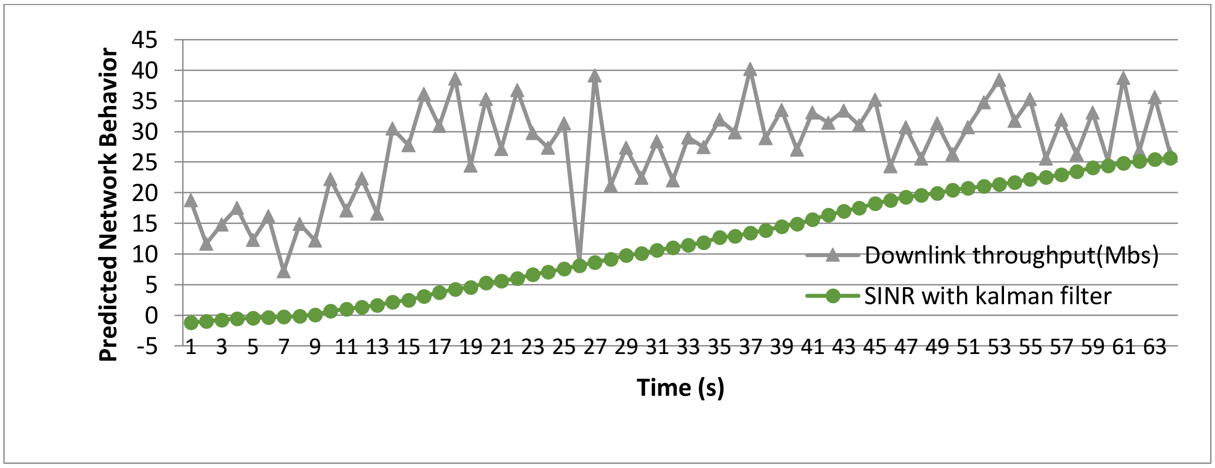


Figure 6: Kalman filter predicted bandwidth availability

The figure 6 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.

5.1**Performance of the Kalman Filter based sliding window link control algorithm**

This section shows the results of the link control algorithm based on Kalman Filter shown in figure 1. The algorithm optimized the link control of the 4G network by predicting the network behaviour, adapting in real time, and enhancing performance. It estimated critical parameters like SINR and BER, etc. accurately, helping the link control algorithm to make smart and adaptive choices. The filter's real-time tracking abilities enabled fast responses to changing network conditions, such as interference and channel variations. The link control algorithm based on Kalman Filter reduced measurement noise and provided a more stable and focused connection between link control metrics, reducing the scattering effect. The simulation used performance indicators such as spectral efficiency, bit error rate, block error rate and throughput to evaluate the Kalman filter algorithm.All results were reported in the tables 1-4

TABLE 1: VALUES FOR THE PLOT OF SPECTRAL EFFICIENCY OF THE NETWORK LINK WHEN THE PROPOSED KALMAN FILTER BASED WINDOW FLOW LINK CONTROL ALGORITHM WAS USED IN THE SIMULATION.

Spectral efficiency(bps/Hz)	**SINR(dB)**
0.3174	-1.2319
0.3503	-0.9778
0.3926	-0.7520
0.4350	-0.6109
0.4350	-0.4980
0.4444	-0.3569
0.4538	-0.2722
0.4773	-0.1310
0.5243	-0.0181
0.5948	0.2641

TABLE 2: VALUES FOR THE PLOT OF BIT ERROR RATE OF THE NETWORK LINK WHEN THE PROPOSED KALMAN FILTER BASED WINDOW FLOW LINK CONTROL ALGORITHM WAS USED.

Bit Error Rate	**SNR(dB)**
0.7681	0.0282
0.7695	0.0734
0.7681	0.2879
0.7653	0.4234
0.7639	0.5589
0.7469	0.7734
0.7469	0.9202
0.7441	1.0782
0.7371	1.4169
0.7314	1.6992

TABLE 3: VALUES FOR THE PLOT OF VARIATION OF BLOCK ERROR RATE WHEN THE PROPOSED KALMAN FILTER BASED WINDOW FLOW LINK CONTROL ALGORITHM WAS USED

Block Error Rate	**Transport Block Size(bits)**
0.5351	31.9355
0.5055	50.6452
0.5011	62.9032
0.5055	82.9032
0.4946	91.2903
0.5149	120.3226
0.5181	131.2903
0.5181	148.0645
0.5116	158.3871
0.5055	171.9355

TABLE 4: VALUES FOR THE PLOT OF DOWNLINK THROUGHPUT WHEN THE PROPOSED KALMAN FILTER BASED WINDOW FLOW LINK CONTROL ALGORITHM WAS USED.

Downlink throughput(Mbs)	**Time(s)** $\times \mathbf{1.0e+0.3}$
15.4506	0.0032
19.2359	0.0135
19.5650	0.0355
18.5776	0.0626
19.3456	0.0781
22.8017	0.0923
19.5102	0.1245
20.0039	0.1335
30.9757	0.1852
36.5165	0.2161

6. CONCLUSION AND RECOMMENDATION

This paper has successfully applied Kalman filter-sliding window based controller to improve controller adjustment in wireless network in order to improve link control. This proposal was designed and implemented with MATLAB, and then tested through simulation methodology. The combined improvements in throughput, spectral efficiency, and reduction in bit error and BLER 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-sliding window 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.

6.1 **Recommendation**

Traffic trace data-set is essential for obtaining the model that accounts for the evolution of the network traffic. This is essential for any realistic use of simulations to conduct research into data link control improvements. It is usually hard to obtain enough categorized and structured data with the desirable characteristics. Therefore, it is the recommendation that, in further studies, the use of big data and machine learning techniques can be set up to generate enough appropriate synthetic traffic trace data for use. In an actual implementation, it is recommended that an Application Specific Integrated Circuit (ASIC) based implementation of the Kalman Filter algorithm should be used. This should be considered for faster and optimized real-time execution of the estimation and prediction steps of the Kalman filter.

7. REFERENCE

Krieger U., & Kumar B., (2018) Modeling the Performance of ARQ Error Control in an LTE Transmission System.

Jain R. (2014) A Timeout-Based Congestion Control Scheme for Window Flow-Controlled Networks. *IEEE Journal on Selected Areas in Communications*, pp. 23-19.

Sastry A., (2018) Intelligent data link signaling control for high throughput in frame relay networks. *Queue*, 14(5), 50.

Adesh N., & Renuka J., (2019) Adaptive Receiver-Window Adjustment for Delay Reduction in LTE Networks. *Journal of Computer Networks and Communications*, Volume 2019, Article ID 3645717, 17 pages. https://doi.org/10.1155/2019/3645717

MatíasT., RocíoA., Almudena S., Salvador L.,& Carlos Ú., (2017) Estimating SpectralEfficiency Curves from Connection Traces in a Live LTE Network. *Hindawi Mobile Information Systems*, Volume 2017, Article ID 7969102, 11 pages. https://doi.org/10.1155/2017/7969102.

Gerla, M., & Kleinrock, L. (1980) Flow Control: A Comparative Survey. *IEEE Transactions on Communications*.

Kozo Sa., Eiji Takahashi, Takeo Onishi, Takayuki Suzuki, Daisuke Ohta, Kosei Kobayashi, and TutomuM. (2020). Passive Method for Estimating Available Throughput forAutonomous Off-Peak Data Transfer. *Hindawi Wireless Communications and Mobile Computing*, Volume 2020, Article ID 3502394, 12 pages. https://doi.org/10.1155/2020/350239.

APPENDIX A (MTN NIGERIA LTE NETWORK RADIO LINK TRANSMISSION TRACE DATA FOR USER EQUIPMENT (UE) AND ENODEB)

TimestMTNmp	Longitude	LMTNtitude	Speed	OperMTNtornMTNme	CellID	NetworkMode	RSRP (dBm)	RSRQ (dB)	SNR (dB)	CQI	RSSI (dBm)	DL_bitrMTNte	UL_bitrMTNte	StMTNte	NRxRSRP	NRxRSRQ	ServingCell_Lon	ServingCell_LMTNt	ServingCell_DistMTNnce
0247002470.11.02471_15.03.50	7.5036	6.4403	0	MTN	247	LTE	-95	-11	4	10	-80	0	0	D	-	-	-8.49172	51.89391	551.37
0247002470.11.02471_15.03.51	7.5036	6.4403	0	MTN	247	LTE	-95	-11	247	8	-78	0	0	I	-	-	-8.49172	51.89391	551.37
0247002470.11.02471_15.03.50247	7.5036	6.4403	0	MTN	247	LTE	-95	-11	13	9	-80	0	0	I	-	-	-8.49172	51.89391	553.4025
0247002470.11.02471_15.03.50247	7.5036	6.4403	0	MTN	247	LTE	-95	-11	13	9	-80	0	0	I	-	-	-8.49172	51.89391	553.4025
0247002470.11.02471_15.03.53	7.5036	6.4403	1	MTN	247	LTE	-95	-13	13	9	-80	0	0	I	-	-	-8.49172	51.89391	563.48
0247002470.11.02471_15.03.53	7.5036	6.4403	1	MTN	247	LTE	-95	-11	13	9	-80	0	0	I	-	-	-8.49172	51.89391	563.48
0247002470.11.02471_15.03.54	7.5036	6.4403	1	MTN	247	LTE	-97	-13	-247	9	-80	0	0	I	-	-	-8.49172	51.89391	563.48
0247002470.11.02471_15.03.55	7.5036	6.4403	1	MTN	247	LTE	-97	-13	-247	9	-80	247149	83	D	-	-	-8.49172	51.89391	563.48