Energy-Efficient Communication Protocols for Green Wireless Networks: Algorithms, Strategies, and Real-World Implementations

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Abstract

With the surging demand for wireless communication, the need for energy-efficient and sustainable network solutions has emerged to be increasingly critical. The paper primarily delves into the development and optimisation of energy-efficient communication protocols designed to reduce the power consumed in wireless networks while still maintaining reliability and high performance. Through a comprehensive analysis of diverse network components, including mobile device base stations, and data transmission processes, the study concentrates on the development of algorithms that minimise the energy consumed to a significant extent. Fundamental strategies taken into consideration range from coding and adaptive modulation, sleep mode techniques and energy-aware routing. The use of machine learning (ML) algorithms, especially in reinforcing learning and predictive analytics, paves the way for dynamic adjustment of network parameters in terms of real-time traffic conditions and user behaviour. Integrating renewable energy inclusive of an array of sources like solar and wind into wireless network infrastructures is also explored and examined, paving a way for both resilience and sustainability against power grid failures. Experimental

evaluation and the simulation reveal that the proposed energy-efficient protocols may significantly minimise the power consumed but still not compromise with the quality of service (QoS) provided. The findings demonstrates the pivotal role of energy efficiency in the evolution of next-generation wireless networks alongside the provision actionable insights for network operators, designers, and policymakers.

1.0: Introduction

The dramatic rise in the expansion of wireless communication networks, driven by the surge in the proliferation of the Internet of Things (IoT), and mobile devices has resulted in a corresponding increase in the energy consumed (Bernardo et al., 2015). Traditional wireless networks, usually characterised by their relatively higher energy demands, prove unsustainable in the long range as a result of their operational costs and environmental impact (Boukerche, Wu, & Sun, 2019; Ren, Zhang, & Lu, 2020). As worldwide energy resources proceed to strain, there is a call for the need for communication protocols prioritising energy efficiency in the maintainace of needed performance levels and reliability.

Energy-efficient communication protocols are mainstream in the development of promising solutions to addressing such problems. Typically, the optimisation of the usage of energy in typical network components, and the underlying protocols may end up reducing the ultimate power consumption as far as the wireless networks are concerned (Sheng, & Liu, 2014). The paper primarily explores how such protocols may be developed following multifaceted strategies like adaptive modulation and coding, sleep mode techniques and energy-aware routing.

2.0: Literature Review

Studies have established that the integration of renewable energy sources, like wind and solar, into wireless network infrastructures is ideal for fostering sustainability and efficient energy utilisation (Ezeigweneme et al., 2024). Considering this research, there exists an opportunity to use renewable energy sources in powering various network components. As such, this will significantly minimise reliance on traditional sources of energy. According to (2021), the most appealing applications of renewable energy are incorporated in wireless networks in utilising solar power in executing operations in base stations. Equipping base stations with solar panels has been known to limit overreliance on the electrical grid as well as a relatively lower ultimate carbon footprint (Ernst, 2012).

Considering one of the case studies, solar panels were installed at several base stations. This was followed by monitoring the energy consumed and performance for approximately six months. The results indicated that solar-powered base stations have the capability of providing a reliable and sustainable source of renewable energy, even in areas with limited sunlight (Stephanie, & Karl, 2020). Broadly, the energy saved by using solar power was indeed significant. As such, this was considered a viable alternative for the reduction of the negative impact towards the environment relative to wireless networks (Sheng, & Liu, 2014).

Apart from solar power, studies have also pointed out the significance of wind energy as far as wireless network renewable sources of energy are concerned. Wind turbines have been deployed and installed at base stations or subsequent network components to generate electricity from wind (Li, 2022). In this study, the case taken into account constitutes an incidence where wind energy through simulation was integrated into wireless networks to ascertain their performance in typical environmental conditions while considering elements including turbine efficiency, speed of wind and capacity of energy stored (Gandotra, & Jha, 2017). The results showcased that wind energy is complementary to solar power in light of providing a sustainable source of energy in wireless networks. With a combination of solar and wind energy, it is possible developing an entirely resilient and energy-efficient network infrastructure (Bhuiyan, 2022).

3.0: Methodology

The research aims to develop energy-efficient communication protocols by adopting the following methodologies:

3.1. Adaptive Modulation and Coding

Adaptive modulation and coding (AMC) plays a fundamental role in minimising the consumption of energy in wireless networks. This is confined to the assumption that it may appropriately adjust the modulation and coding schemes following real-time channelling conditions (Lye et al., 2012). For example, in incidences where channel conditions are depicted as favourable, the usage of higher-order modulation schemes can help in the transmission of additional data with similar energy (Boukerche, Wu, & Sun, 2019).

Contrarily, channel conditions deterioration, may call for the adoption of relatively lower-order modulation schemes. This will be vital in the maintainace of transmission integrity while at the same time helping in energy conservation. The algorithm created for such an objective is primarily dependent on the feedback loop. In such a circumstance, the receiver monitors the conditions of the channel continuously while simultaneously communicating them back towards the transmitter (Ding et al., 2021). Thereafter, the transmitter will end up adjusting accordingly following its coding and modulation scheme. The underlying varying adjustment often in the long range significantly improves the efficiency of energy while still maintaining the anticipated quality of service (QoS) by paving the way for entirely reliable data transmission.

The AMC model may be mathematically represented following the Hartley theorem. It primarily relates the maximum data rate achievable to the bandwidth and the communication channel signal-to-noise ratio (SNR) (Johnson, 2006). Considering the theory, the efficiency of energy (η) is expressed as the ratio of the data rate (R) to the consumed energy (E). The relationship can be described by Equation (1)

$$\eta = \frac{R}{E} = \frac{B \cdot \log_2(1 + \mathrm{SNR})}{P} \qquad (1)$$

- B denotes bandwidth,
- SNR is the signal-to-noise ratio
- P is the power consumed.

The modulation order M adjustment of the AMC algorithm typically following the conditions of the channel, aims to maximise η. The algorithm typically executes its operations as follows:

- **Initialisation:** It entails setting initial modulation order M_0 alongside coding rate R_0 followingthe average channel conditions.
- **Channel Estimation**: Involves estimating the channel conditions continuously in calculating the prevailing SNR.
- **Adjustment of Modulation:** With an improvement of SNR, increase M; if it deteriorates, reduce M.
- **Coding Rate Adjustment**: Consequently, adjust the coding rate R to maintain a balance between error rate and energy efficiency.
- **Energy Efficiency calculation**: Calculate η while at the same time updating the coding parameters altogether with modulation to maximise η.

Finally, the model will be instrumental in having a detailed theoretical foundation regarding the trade-offs in the energy consumed, QoS and ultimate performance of the network (Ren, Zhang, & Lu, 2020). Figure 1 illustrates the relationship between SNR and energy efficiency for an AMC algorithm showcasing how efficiency of energy improves with an increase I SNR and how the algorithm adjusts the modulation in optimising performance.

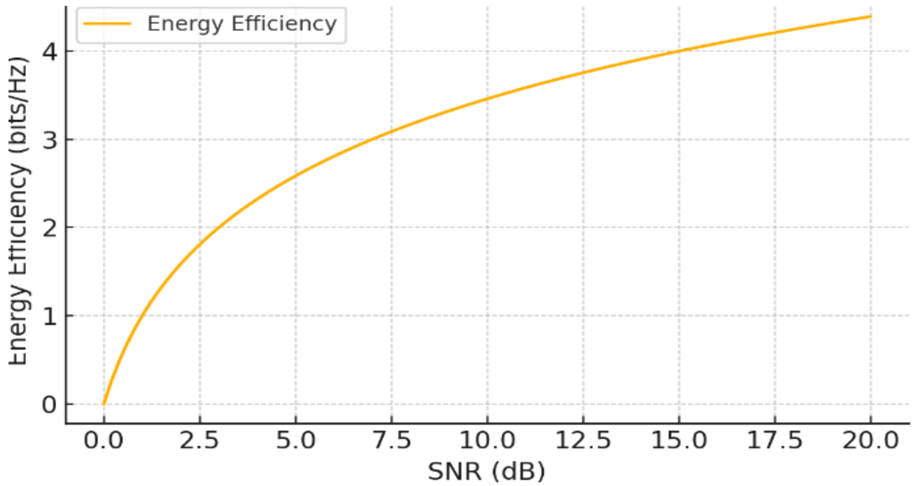

Figure 1.0: SNR for AMC versus Energy Efficiency

3.2: Energy-Aware Routing (EAR)

The purpose of energy-aware routing (EAR) protocols is to extend the battery life of mobile devices while reducing the ultimate energy consumed by specific networks (Banerjee & Hussain, 2018). Tentatively, this is achieved through the selection of routes that may significantly limit the energy consumed in the course while considering a myriad of factors including the energy needed for transmission, battery life nodes remaining, and the opportunity to harness energy.

In the model, the implementation of the EAR protocol is achieved by using the reinforcement learning algorithm. This element continuously learns through the influence of the network environment, adapting towards the routing decisions at the same time following real-time conditions (Banerjee, & Hussain, 2018). At times, for instance, the algorithm may prioritise routes that pass through nodes with substantial amounts of energy resources or those harnessing energy from renewable energy sources (Chen et al., 2011).

An assessment of the efficiency of the EAR protocol is achieved through simulations. This is then followed by comparing traditional routing protocols. The results showcase a substantial reduction in the energy consumed, particularly in incidences characterised by high network traffic as depicted in table 1.

Table 1: Comparison of Energy Consumption in Distinct Routing Protocols

Routing Protocol	Energy Consumption (joules)	Network Traffic (Mbps)
Prosed EAR protocol	250	50
Traditional routing 1	350	50
Traditional Routing 2	400	50

The following algorithm for the EAR protocol which is based on a reinforcing learning framework in which the network learns the optimal routing path continuously relative to the QoS and energy consumption metrics is adopted:

- **Representation of State**: The state S_t at time *t* denotes the nodes of energy levels, the traffic load and remaining battery life.
- **Selection of Action**: The action A_t corresponds to the selection of the subsequent hop in the routing path. The

selection is confined to a policy π aiming to reduce the consumption of energy while meeting the requirements of QoS.

- **Reward Function**: The reward R_t is denoted as a function of the saved energy and the QoS achieved. The reward function can be described by Equation (2):

$$R_t = -E_t + \lambda \cdot \mathrm{QoS}_t \quad (2)$$

Whereby E_t prescribed consumed energy, Q_oS_t denotes the quality of service, and λ represents the weighting factor balancing energy efficiency and QoS.

- **Policy Update**: The policy π is updated using a Q-learning reinforcement learning algorithm that over time maximises the cumulative reward.

3.3. Sleep Mode Techniques

Sleep mode techniques are primarily designed to minimise the energy consumed by various components of a network by placing them into a low-power state when they are not actively receiving or transmitting data (Ashraf, Boccardi, & Ho, 2011). These techniques have proved worthwhile in minimising the energy consumed at base stations, where among the highest energy consumers is in wireless networks. In this study, the development of the sleep mode algorithm is confined towards a predictive model anticipating periods of limited network activity (Mohamed et al., 2018). Undertaking a detailed analysis of various historical traffic patterns at the same time while making use of ML techniques, the algorithm is in a position to predict when a base station or subsequent network component is placed in sleep mode without posing any significant effect on network performance.

The sleep mode algorithm simulation demonstrates its efficiency in minimising the energy consumed, specifically in networks with ever-changing traffic patterns (Ashraf, Boccardi, & Ho, 2010). The results showcase substantial energy saved but still, the QoS remains steadfast. Figure 2 illustrates the results obtained from the simulation for the sleep mode techniques, displaying the energy saved during various periods of relentlessly low network activity. It showcases the predictive model efficiency within accurately anticipated periods of low activity minimising the energy used.

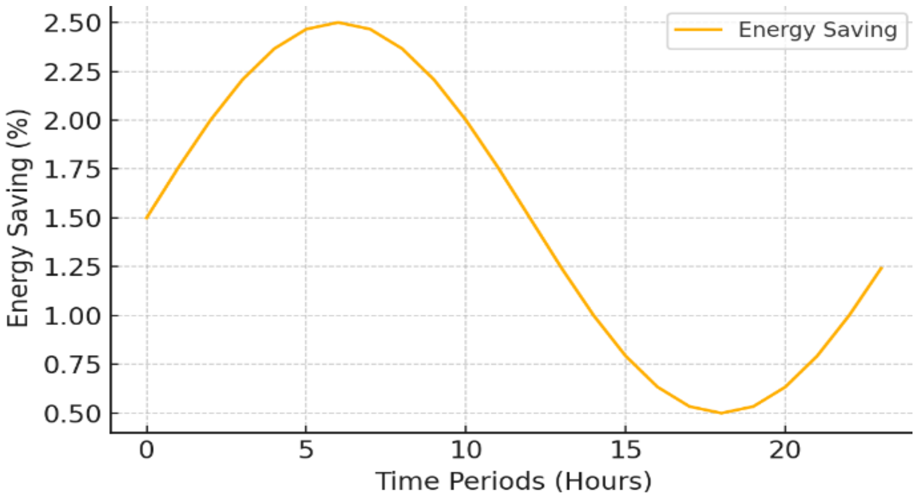

Figure 2: Simulation Results for Sleep Mode Techniques

4.0. Experimental Evaluation, Results and Discussion

An evaluation of the proposed energy-efficient communication protocols is examined by several real-world examinations and simulations. This section presents the findings of a typical evaluation, pinpointing the achieved energy savings alongside the impact of the performance of the network.

4.1. The Setup of the Simulation

The implementation of the simulation took into account a custom-built networking simulator modelling the behaviour of wireless networks in diverse conditions. The underlying configuration of the simulator is imperative in assessing the performance protocol proposed based on the reliability of the network, QoS, and the energy consumed. The simulation scenario primarily adopts both urban and rural environmental conditions which significantly vary with diverse network traffic levels. As far as the simulation is concerned, the adopted parameters are confined to the collected real-world relative to the existence of wireless networks.

4.2. Energy Savings and Quality of Service (QoS)

The study findings showcase that the proposed energy-efficient communication protocols tend to harness far much higher energy savings far much higher compared to traditional protocols. Considering scenarios associated with low traffic levels, the energy saving is above 40%. Contrarily, in high network traffic, the energy savings are approximately 20% to 30% (Behera et al., 2022).

In essence, the AMC technique has been discovered to be more efficient since it significantly reduces the consumed energy, especially in places where channel conditions fluctuate. On a similar prospect, the EAR protocol also saves a significant amount of energy through the selection of routes with the capability of reducing the consumed energy. The consideration of the sleep mode techniques is entirely effective in minimising the base station energy consumption. This is especially critical in networks with limited activities (Pradhan, & Rajeswari, 2021).

Other than energy being saved, it is evident that the proposed protocol at the same time will primarily maintain a relatively higher level of QoS. From the findings, it is evident the simulation protocols have the capability of achieving achieve required data transmission rates, and latency alongside, reliability, even in situations which are have entirely challenging networks.

5.0: Conclusion

5.1: Summary

The study evaluated energy-efficient communication protocols implementation framework in light of green wireless networks. The findings relative to the proposed protocols, which incorporated AMC, sleep mode techniques and EAR, showcase that they have the capability of leveraging and saving a significant amount of energy consumed without compromising the performance of the underlying network. In essence, integrating renewable sources of energy including solar and wind, will ultimately exacerbate the sustainability as far as wireless network is concerned. With this in place, it will pave the way for an ideal pathway for reducing their action in terms of their carbon footprint impact. In the study, the simulation together with examined case studies validates the efficiency and effectiveness of the proposed protocols in diverse scenarios in the real world.

5.2. Future Direction

The study provides a comprehensive account of the implementation of energy-efficient communication protocols. However, there still exist areas that may need future exploration. These include the following:

- There is a need for integrating sophisticated ML techniques, including neutral networks and deep reinforcement learning. This may consequently optimise the performance of the proposed protocols.
- There is a need for integration with emerging technologies. Typically new technologies including edge computing, 6G, and blockchain emerge, and there will be opportunities for integrating energy-efficient communication protocols with such innovations.

6.0: References

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