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Wind Energy Dependent Rate Adaptation for Roadside Units

George A. Audu, Samya Bhattacharya and Jaafar M. H. Elmirghani
School of Electronic and Electrical Engineering, University of Leeds, UK
elgaa@leeds.ac.uk, s.bhattacharya@leeds.ac.uk and j.m.h.elmirghani@leeds.ac.uk

Abstract—**In this paper, we propose a rate adaptive technique for wind powered standalone (off-grid) roadside units (RSUs) in a motorway environment. In a non-rate adaptive system, the transient nature of renewable wind energy causes the RSUs to either transmit at full data rate or not transmit at all based on the availability of sufficient energy. In rate adaptation, the data rate of an RSU adapts according to the available energy. Further, the RSU saves transmission energy by operating at a lower data rate, even when enough energy is available. The saved energy, in turn, is used to maintain the data rate during energy deficiency, thereby minimizing outage and improving the quality of service (QoS). The performance analysis shows that the wind energy dependent rate adaptive RSU delivers a more energy efficient service with acceptable quality compared to a non-rate adaptive deployment in a renewable energy solely powered RSU. The proposed rate adaptive algorithm can be as well deployed to wind-powered communication base stations (BSs) and sensor networks.**

Keywords—Roadside unit; motorway; renewable energy; adaptive rate..

I. INTRODUCTION

Deployment of renewable energy sources for vehicular networks has recently become an area of research interest since the use of environmentally sound communications as well as power aware network architecture and protocols design are imperative [1-3]. In [4, 5] MAC protocols which are based mainly on communication channel quality have been proposed for vehicular networks. In a traditional non-adaptive RSU deployment, the RSU operates at a fixed data rate only when it has sufficient power and ceases to function otherwise. Our wind energy based rate adaptive technique allows the RSU to transmit at various data rates based on the available wind energy while maintaining an acceptable level of QoS. Such RSUs not only reduce the carbon footprint of vehicular networks but also are easily deployable.

The intermittent nature of renewable energy resources (such as wind and solar energy sources) has led to the need of incorporating energy storage devices such as fast rechargeable battery. Although there is no control over wind power availability, its usage at any time is controllable when a proper battery is used [6]. The reliability of the proposed RSU is therefore enhanced by incorporating a battery, which stores excess wind energy to cater for energy deficiency. In this paper, we propose a rate adaptation technique, where an RSU transmits data at various rates according to the available wind energy. The transmitting data rates are obtained through the proposed rate adaptation algorithm for given available wind energy and stored energy. This improves quality of service by reducing the outage (due to energy deficiency) of the RSU. Finally, the performance of the RSU with the proposed rate adaptation is compared with that of the non-adaptive RSU.

Following the introduction, the remainder of the paper is organized as follows. Section II describes the proposed scenario with system parameters. Section III contains the wind energy model and RSU load model. The rate adaptation algorithm is described in Section IV. Section V discusses the performance results. Finally, the paper concludes in Section VI.

II. THE MOTORWAY SCENARIO

We consider a three lane motorway (considering one direction of travel), where the RSUs are installed 1 km apart as shown in Fig. 1. This conforms to the Wireless Access for Vehicular Environment (WAVE) standard [7]. The RSUs receive data from moving vehicles and relay the information to a base station that is beyond the transmitting range of the vehicles. The RSU is connected to a micro turbine for wind power generation through a compact chargeable battery. A small battery capable of supplementing the wind energy deficit is utilized to deliver an acceptable quality of service with rate adaptation. The small battery size enhances ease of deployment and maintenance of the off-grid RSUs in a motorway scenario. The performance of the proposed RSU is investigated by focusing on one of the RSUs. The system parameters are shown in Table 1.

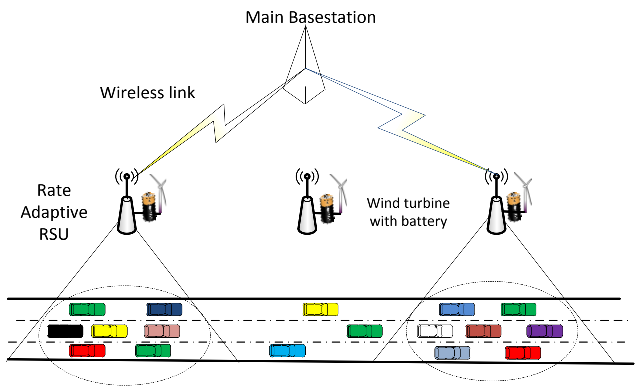

Fig. 1. Proposed rate adaptive RSUs in a motorway.

TABLE I: SYSTEM PARAMETERS

Parameters	Values
Micro turbine propeller length (diameter D)	1 m [8]
Swept area (A)	0.785 m^2 [8]
Coefficient of performance (C_p)	0.45 [8]
Air density (ρ) at 15℃	1.225 kg/m^3 [9]
Cut-in speed	3.5 m/s [10]
Cut-out speed	21 m/s [10]
Vehicle data generation rate (d_t)	320 kbps [11]
Maximum data rate (d_{r_Max}) of RSU	27 Mbps [12]
Average packet size	867.4 bytes [11]
RSU max. power consumption (P_{Max})	20 W [12]
RSU operational power (P_{op}^{RSU})	P_{Max}/1.3548 [13]
Maximum transmit power (P_{Tx-max})	$P_{Max} - P_{op}^{RSU}$ [13]

III. WIND ENERGY MODEL AND RSU CONSUMPTION

In order to develop a model for the wind energy obtained from the micro-turbine of the off-grid RSU, hourly average wind speed samples measured at the Newtown (Reading, UK) measuring site for a period of five years have been obtained from the UK air information resource (AIR) database provided by the Department for Environment Food and Rural Affairs [9]. The samples were used to obtain the probability distribution of wind speed which follows Weibull distribution. Several authors have proposed Weibull distribution as an acceptable wind speed model [14-16]. The Weibull parameters of the hourly wind speed samples are used to obtain the instantaneous wind speed and power models. Samples of instantaneous wind speed for each hour of the day are generated using a Matlab Weibull random variable generating function (wblrnd (α, β)) where α is the scale parameter in m/s, and β is the unit-less shape parameter of Weibull distribution. The Weibull pdf of wind speed is given as

$$f_v(v) = \frac{\beta}{\alpha}\left(\frac{v}{\alpha}\right)^{\beta-1} e^{-\left(\frac{v}{\alpha}\right)^{\beta}} \qquad v \geq 0 \tag{1}$$

where v is the instantaneous wind speed in m/s. The mean speed can be expressed as a function of α and β as

$$v_{mean} = \mu_v = \alpha\Gamma\left(1+\frac{1}{\beta}\right) \tag{2}$$

Figure 2 shows the pdf of instantaneous wind speed.

The instantaneous power obtained from the wind can be expressed as [8]

$$P_w = \frac{1}{2} C_p \rho A v^3 \tag{3}$$

where ρ is the air density (in kg/m^3); A is the swept area (in m^2) of the micro turbine; v is the wind speed (in m/s) normal to A; and C_p is the coefficient of performance of the wind turbine which accounts for the decrease in the actual power harnessed from the wind due to several factors such as, rotor and blade design that lead to friction and equipment losses. The parameters are shown in Table I.

We obtain the wind power pdf by transforming the wind speed random variable to wind power random variable. Since the wind power is cubic proportional to the wind speed according to (3), i.e., $P_w = g(v)$, where g is a monotonic

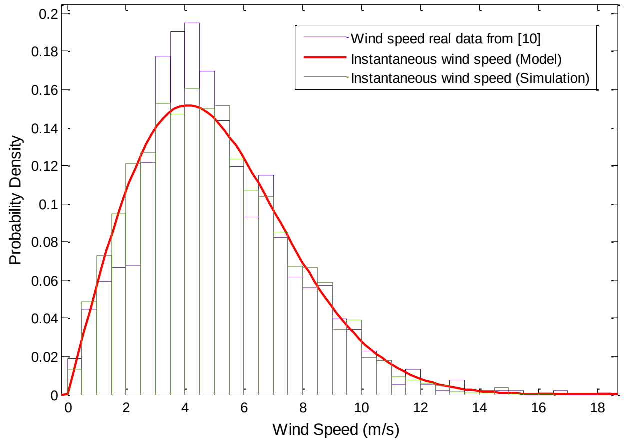

Fig. 2. Model validation of instantaneous wind speed.

function, and v has a pdf of $f_v(v)$, the pdf of instantaneous power ($f_p(P_w)$) in terms of v and $f_v(v)$ can be expressed as [17]

$$f_p(P_w) = \left|\frac{1}{g'(g^{-1}(v))}\right| f_v\left(g^{-1}(P_w)\right) \tag{4}$$

where g^{-1} denotes inverse and g' derivative of g. If (4) is applied to the speed pdf in (1), the pdf of the power may be expressed as a function of the variable, P_w, considering its relationship with the wind speed v in (3) as

$$f_P(P_w) = \frac{\beta}{3c_t\alpha^3}\left(\frac{P_w}{c_t\alpha^3}\right)^{(\beta/3)-1} e^{-\left(\frac{P_w}{c_t\alpha^3}\right)^{\beta/3}} \tag{5}$$

where $P_w \geq 0$ and $c_t = A\rho C_p/2$. Equation (5) can be expressed as a Weibull distribution

$$f_P(P_w) = \frac{\beta'}{\alpha'}\left(\frac{P_w}{\alpha'}\right)^{\beta'-1} e^{-\left(\frac{P_w}{\alpha'}\right)^{\beta'}} \tag{6}$$

where

$$\alpha' = \frac{1}{2}A\rho C_p\alpha^3 \qquad \beta' = \frac{\beta}{3}$$

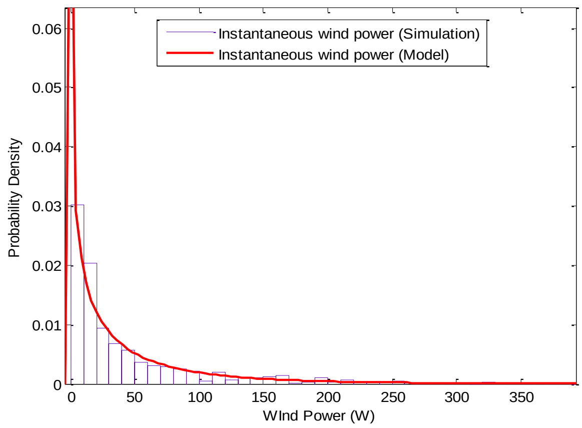

Fig. 3. Model validation of instantaneous wind power.

Figure 3 shows the pdf of the instantaneous wind power. The mean power can also be expressed as a function of parameters α' and β' of Weibull distribution as

$$P_{w_{mean}} = \mu_p = \alpha'\Gamma\left(1 + \frac{1}{\beta'}\right) \quad (7)$$

The total power consumption of the RSU comprises of transmission energy per unit time and the fixed power consumed by the RSU circuitry which is the minimum operational energy per unit time (P_{min}). The transmission energy of RSU is the energy used mainly in transmitting packets in the vehicular network. This constitutes the RSU load which varies hourly according to the vehicular density. The hourly RSU load or transmission energy therefore is Gaussian distributed. This is because the packet generation from vehicles follow Poisson distribution [11]. Since the energy per bit is fixed, the energy required by the RSU to transmit the arriving Poisson distributed packets is Gaussian distributed in continuous domain. Gaussian distribution is an excellent approximation of Poisson distribution when the total number of events becomes sufficiently large [18]. This is confirmed by the central limit theorem which states that the distribution of the sum (or average) of a large number of independent, identically distributed variables will be approximately normal, regardless of the underlying distribution.

Since the operational energy per unit time is fixed, the probability density function of the RSU energy consumption model can be expressed as

$$f(P_L) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{((P_L - P_{min}) - \mu)^2}{2\sigma^2}} \quad (8)$$

where the random variable P_L denotes the total energy consumption of the RSU per unit time. The parameters μ and σ represent the mean and variance of the transmission energy consumption.

In case of a non-rate-adaptive RSU, the total power consumption can be expressed as

$$P_{NRA}^{RSU} = P_{min} + P_{Tx-max} \quad (9)$$

where P_{Tx-max} is the maximum transmission power of the RSU. In this scenario the RSU either transmits at full data rate using the maximum transmission power or ceases to transmit based on the availability of P_{Tx-max}. This results to several moments of transmission outage in situations where the energy source is purely renewable (as in our deployment) considering its transient nature. In rate-adaptive RSU, the total power consumption can be expressed as

$$P_{RA}^{RSU} = P_{min} + P_{Tx-var} \quad (10)$$

where P_{Tx-var} is the variable transmission power whose value depends upon the available energy for transmission. In order to obtain a transmitting data rate for each instance of P_{Tx-var}, the transmitting energy per bit was obtained from the transmitter power (P_{Tx-max}) and the maximum data rate (27 Mb/s). Weibull power was generated, P_{min} was subtracted from this power, and the remaining part if above zero was used with the energy per bit value to determine the data rate, hence generating Figs. 4 and 6. The adaptive data rate (d_{Tx-var}) is linearly proportional to P_{Tx-var} since the transmitting energy per bit (J/s) is fixed for transmitters. [19].

IV. Rate Adaptive Technique

The first step for rate adaptation is to obtain the wind energy available for transmission (E_{Tx-var}). This is essentially the difference between instantaneous wind energy available (E_w) and the RSU operational energy consumption (P_{min}). A positive E_{Tx-var} implies that the wind energy is sufficient to enable the RSU to transmit at certain data rates depending on the magnitude of E_{Tx-var}. If E_{Tx-var} is negative, the RSU draws the transmission energy from the battery. A small battery of 27 Ah with 50% depth of discharge (DOD) (about half size of an automobile battery) is used in this deployment [20]. The amount of energy drawn is N% of the maximum capacity of the battery. The parameter N is Normal distributed. If E_{Tx-var} is positive and greater than the maximum transmission energy (E_{Tx-max}), then the surplus and S% of E_{Tx-max} is used to charge the battery. The parameter S is also a Normal distributed variable. The parameters N and S in the designed adaptive rate algorithm are Normal distributed for the reason that the transmission energy (RSU load) is Gaussian distributed as explained earlier. Since the load demand is Gaussian distributed, the battery charge and discharge levels are Gaussian distributed and hence N and S are Gaussian distributed.

The corresponding algorithm (Algorithm 1) results in a new transmission energy distribution (E_{Tx-var}) that determines the RSU data rate (d_{r_var}). The adaptive rate algorithm works by computing the transmission energy (E_t) that is obtainable from the generated wind energy (E_w) at each instance of the wind energy sample generated. If E_t is greater than zero and less than the maximum transmission energy ($E_t(max)$), a data rate is computed based on E_t. When E_t is greater than $E_t(max)$, the surplus and S% of $E_t(max)$ is used to charge the battery while the data rate is computed based on the remaining energy. The RSU draws energy (N% of the maximum capacity of the battery) from the battery when E_t is less than zero with the corresponding data rate based on the drawn energy value.

Algorithm 1 for adaptive data rate

Input: E_w, E_{op} *and Load* (E_L)

Output: Data rate

```
for all j ∈ Z do    // Z=total no of samples
    input E_w and E_op;
    Compute E_t;
    if 0 < E_t < E_t(max) then
        compute data rate;
    else if E_t < 0 then
        power RSU with N% of the max battery capacity;
        recompute data rate;
    else if E_t > E_t(max) then
        Charge the battery with surplus and S% of E_t(max);
        recompute data rate;
    end if
end for
```

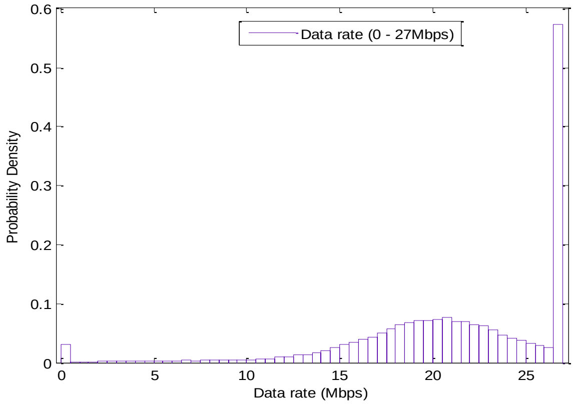

Fig. 4. Complete adaptive rate distribution (0 – 27 Mbps).

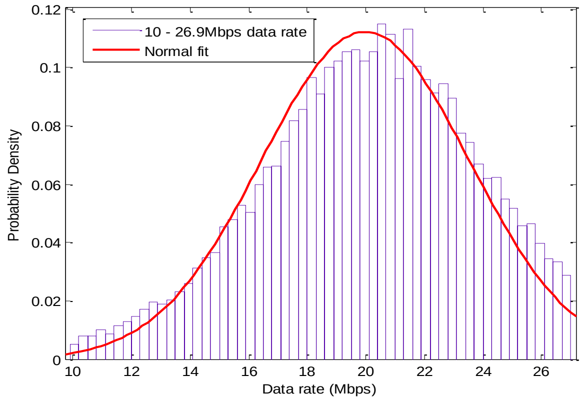

Fig. 5. Adaptive rate distribution for data rate range of 10 Mbps – 26.9 Mbps.

The obtained pdf of the data rate is shown in Figure 4. The data rate distribution is 24.32% 27 Mbps, 67.31% Normal distribution with mean 19.84 Mbps and standard deviation 3.60 Mbps, and 8.37% 2.93 Mbps. Figure 5 shows the mainly Normal distributed portion of Figure 4 (data rate distribution for 10 Mbps – 26.9 Mbps only). Due to the presence of battery coupled with the rate adaptation the Gaussian distribution in Fig. 4 (which is enlarged in Fig. 5 for better view) has larger mean compared to Fig. 6, hence enhancing the service quality of the RSU.

Figure 6 shows the data rate distributions for raw rate adaptation for the operating cases of (1) wind energy only and (2) wind energy with battery. It is evident from Figure 6 that raw rate adaptation in such scenario is fraught with unacceptable RSU outage due to high percentage of zero data rates. In the case of wind energy only, there is high probability of 0 Mb/s data rate and the distribution between 0 Mb/s and 27 Mb/s is also very low due to absence of battery. The RSU transmits only at full data rate (27 Mbps) when it has sufficient transmitting power. This is also true for the case of wind energy with battery without the adaptive rate algorithm that leverages the battery energy (except that it has a lower 0 Mb/s data rate probability and higher 27 Mb/s data rate probability). This is because the data rate varies directly with transmission power which is cubic proportional to the instantaneous wind speed. Hence, a small variation in wind speed presents a huge difference in transmission power and consequently the data rate.

In this work, the QoS is considered mainly in terms of the RSU service availability which directly affects its packet blockage probability and average packet delay. With the proposed rate adaptive algorithm, the RSU has a service outage of only 1% (which represents 99% service availability) while in the two cases of raw rate adaptation the service outages are 8% and 34% for the wind energy only and wind energy with battery respectively.

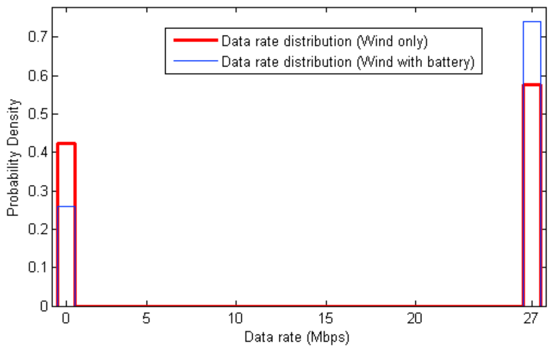

Fig. 6. Data rate distribution for raw rate adaptive RSU.

V. Conclusions

With the primary aim of deploying renewable energy resource which ensures a healthy communications environment with improved energy efficiency, we have proposed rate adaptive RSUs that can be used to tackle the deployment of ubiquitous coverage along a motorway stretch using renewable wind energy. In this paper, we have obtained analytic models for both wind energy and RSU power consumption. These models were used to develop the adaptive data rate algorithm for an RSU in a motorway vehicular network. The performance of the network has been examined with the deployment of a battery (27 Ah with 50% DOD). The proposed wind powered adaptive rate RSU resulted in an improved quality of service (with 21.7% energy saving) when compared with a non-rate adaptive RSU while meeting QoS.

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