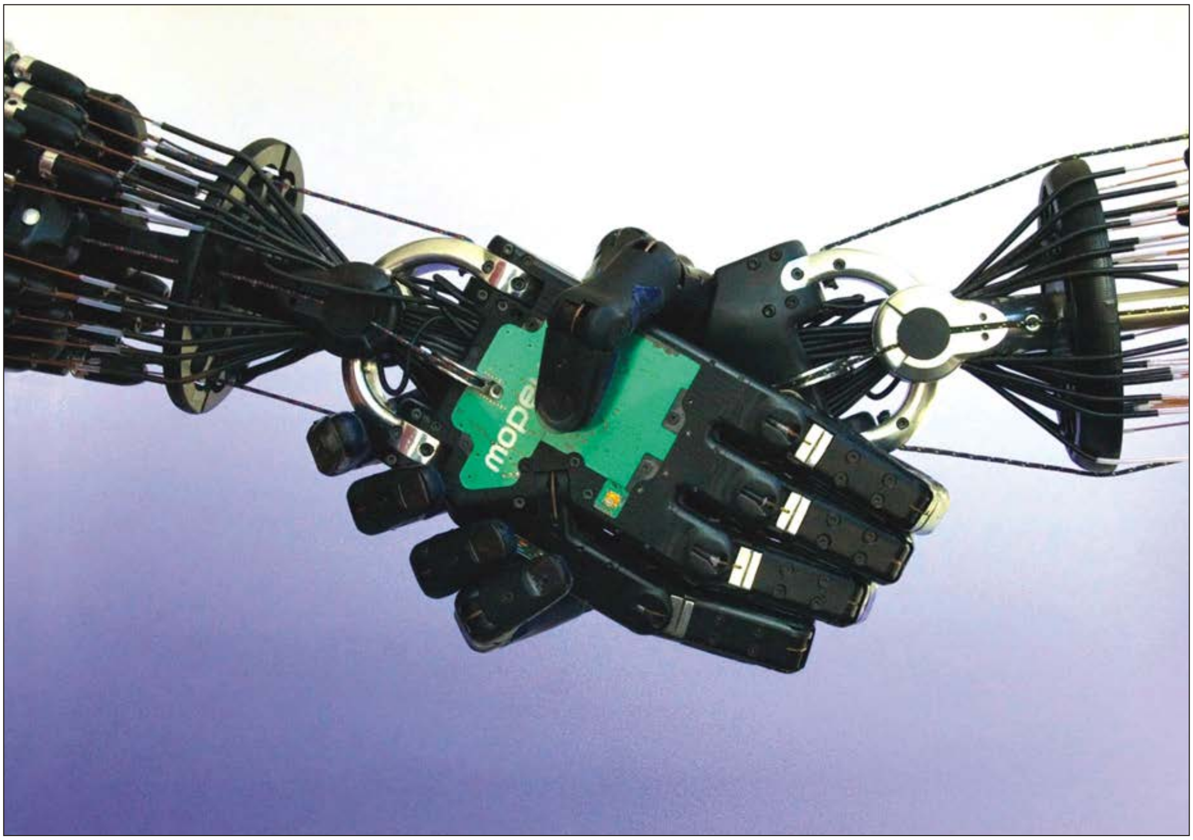

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Research Article
Energy Efficiency of a Dual Hop Clustered Networks in a High Data Rate

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Abstract

This study investigates the energy efficiency of applying hierarchical architecture on to channel constrained next generation wireless networks. Unlike that of LEACH which was designed for sensor networks, this study focuses in a high traffic data applications in which a balance is needed between the throughput, delay and energy consumption. The results are compared to that of a traditional single hop with no hierarchical formation. In order to quantify energy efficiency, Joules per bit otherwise known as ECR (energy consumption rating) metric was a chosen as it provides an insight on how much energy is transferred for one bit of information. It is found that reducing interference can increase the energy efficiency of the dual hop clustered network by 50% and that the network is more energy efficient than the standard single hop if the transmission power dominates the total consumed power by devices coupled with interference mitigating channel assignments schemes. Applying energy saving scheme can also improve the energy efficiency of the network by up to 80%.

Key words: ECR, LEACH, TSB, ECR, SINR

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The energy efficiency of wireless communication networks is attracting considerable interest, as their increasing data rates and ever increasing use mean that they are consuming an ever increasing proportion of the world’s energy usage[1]. Various schemes have been proposed in the literature to tackle the growing concern of energy consumption of radio access network. For example Hoydis *et al.*[2] proposed small cell networks (SCNs) and Niu *et al.*[3] introduced twin state deployments which allow base stations to change state from macro-cell to smaller cells depending upon the traffic load. Accordingly, novel energy efficient centric architectures have also been proposed. The structure of next generation networks is likely to be more *ad hoc* and dynamic in nature in order to cope with a wide range of data requirements, usage, cost and energy consumption. Linked with this is the type of wireless communications architecture, both access and backhaul, that needs to be used with these next generation architectures. For example the FP7 BuNGee project looked at a cost effective dual hop access and backhaul wireless architecture that is capable of delivering 1 Gbps km^{-2} for such future wireless services[4].

This study shall examine the power consumption and efficiency of hierarchical architecture in a dense deployment and high data rate application in more general sense than BuNGee (regular topology) and LEACH (designed for sensor networks)[5]. In this study, nodes collaborate with neighbouring nodes throughs self-organising techniques, in the form of clustering. The operation of a clustering algorithm is such that the nodes are organized into disjoint sets by selecting appropriate nodes as cluster heads h_i or cluster member $n_{i\text{-}j}$. The cluster head will become an access point providing the backhaul links to the networks for its respective cluster members and thus forming a dual hop clustered network as shown in Fig. 1b. Understanding the behaviour and characteristics of such network can aid network designer to optimise its efficiency.

MATERIALS AND METHODS

To accurately analyse the performance of the dual hop cluster networks through simulations, the system model needs to be validated and take into account a number of factors, including the approach to clustering, the propagation model and channel assignment scheme, along with how the received signal to interference plus noise ratio (SINR) is mapped to the transmission data rate. The power control and power consumption model used are addressed and how all the mentioned parameters affect the network radio environment are explained.

Dual hop clustered network upper bound throughput: In the dual hop cluster network scenario, the transmissions from cluster members to cluster heads will be blocked due to inadequate number of uplink channels Q_u available at a particular cluster. Further transmission delayed will be induced if number of backhaul channels Q_b is insufficient for the cluster heads to relay all the concurrent transmissions from its respective cluster members to HBS. All the blocked backhaul transmissions will be buffered at the cluster heads. If the uplink transmissions are not dropped then the rate at which transmissions have to be relayed by cluster heads follow a Poisson arrival rate. Under such scenario, the Erlang C formula $P(b)_c$ given in Eq. 1 enabled the probability that the backhaul transmissions will be delayed to be predicted[6]:

$$P(b)_c = \frac{\dfrac{G^{Q_b}}{Q_b!(1-P)}}{\sum_{i=0}^{Q_b-1}\dfrac{G^{Q_b}}{i!}+\dfrac{G^{Q_b}}{Q_b!(1-P)}} \text{ for } 0<\frac{G}{Q_b}<1 \tag{1}$$

The Erlang C formula assumes that the offered traffic G in Erlang does not exceed the number of available channels, $G<Q_b$. In a high traffic file transfer, whereby the traffic G from cluster member is greater than the number of backhaul channels ($G\geq Q_b$), the cluster heads behaves just like a traffic source in a lossy system with call arrival rate which conforms to a poisson process. Assuming that no transmissions are dropped on the uplink, the expected upper bound throughput $U[S_c]$ for a clustered network to support the offered traffic in bps G_{bps} is:

$$U[S_c]=\begin{cases}0\\ G_{bps}.(1-P(b)_c) \text{ for } 0<G<Q_b\\ G_{bps}.(1-P(b)_c) \text{ for } G\geq Q_b\end{cases} \tag{2}$$

where, $P(b)_b$ is the expected blocking probability under Erlang B formula.

Clustering protocol: The geographical distribution of cluster heads and cluster members generated followed that of the sumRSSI clustering algorithm with a Reward R of 100 with 100 nodes randomly distributed on a square service area of 1,000 × 1,000 m with the HBS in the center of the service area[7]. During the clustering process, the radiated transmit powers of the nodes operate at a maximum power of 0 dB W.

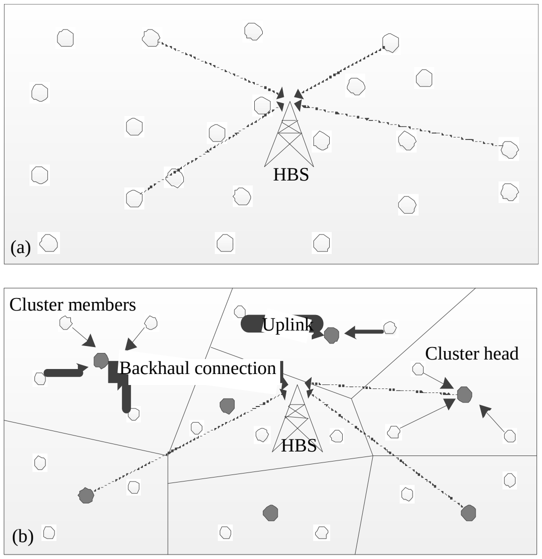

Fig. 1(a-b): Network planning of wireless networks with hierarchical architecture (a) No hierarchical formation and (b) Dual hop clustered network architecture

The cluster heads are assumed to be able to concurrently transmit any number of files if the numbers Q_b are available to support such transmission. Under a high traffic load i.e., when the numbers of backhaul channel is less than the number of concurrent files transmissions, the files will be queued in an infinite size buffer within the cluster heads and the transmission be delayed indefinitely until a channel is available.

Power control: Each node in the network implements an open loop power control based on the signal strength measurements, such as that employed in LTE[8]. Power control is introduced to limit the excessive power and improve the channel utilization by reducing the intra-cluster interference.

All the nodes in the simulated scenarios node were subjected to limit their radiated transmit power such that the SNR at their intended destination is no more or less than 40 dB. The value of SNR target was chosen to provide some margin for expected interference at the receiver, during the life time of the transmission (The TSB mapping operates effectively in an SINR range of 1.8-21dB).

Receive power and path loss model: It is assumed that nodes are located above roof top height so that the height of antenna has relatively small impact on the path loss. The propagation model path loss PL that was used in this study was developed by WINNER II (model B5a)[9]. The amount of power received in logarithmic decibels by node n_i on a particular channel is calculated according to the Eq. 3:

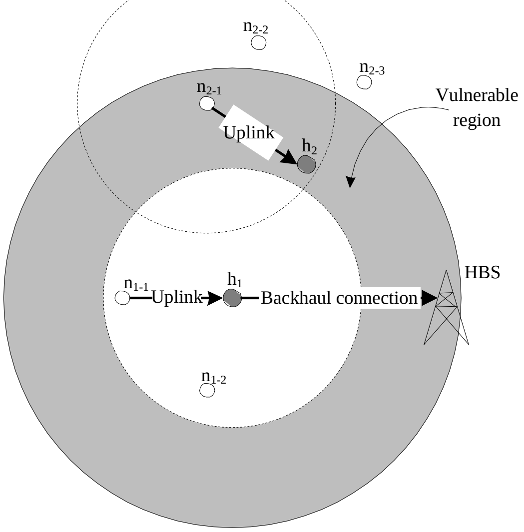

Fig. 2: Shaded area indicates the vulnerable region in which uplink transmissions cannot be detected by cluster head

$$\mathrm{Pr_i\ (dB)=Pd_i(dB)+Gr_i(dB)+Gt_i(dB)-PL_i(dB)} \tag{3}$$

The node antenna patterns are assumed to be isotropic, with their transmitter and receiver gains, $Gt_i = Gr_r = 0$ dBi. The operating frequency is in the 2.1 GHz band and the channel bandwidth is 1 MHz.

Hidden and exposed node terminal problem: In a dual hop clustered network as shown in Fig. 2, the hand shaking protocol does not mitigate the existence of hidden node terminal problem. Consider that power level of node $n_{2\text{-}1}$ is limited such that only its respective cluster head h_2 can successfully receive the transmission. The uplink communication from node $n_{2\text{-}1}$ to h_2 will be 'hidden' from h_1. Node $n_{2\text{-}1}$ is said in vulnerable region since if there is a message to be transmitted via the backhaul link from h_1 to HBS, h_1 will falsely conclude that the channel is empty and began transmission. The newly established transmission from h_1 to HBS will severely disrupt the ongoing communication of node $n_{2\text{-}1}$ to h_2.

Due to the nature of the dual hop clustered architecture, some clusters are located at the edge of the network and the maximum distance of cluster head transmission range (m) assuming a squared network with l side lengths is $\sqrt{\frac{2l^2}{2}}$. The maximum transmission range of cluster heads will affect hidden uplink transmissions within an area of $\frac{\pi l^2}{8}$. It can be seen that the maximum transmission range of cluster heads can cover an area of almost 40% of the network (assuming squared network area). Due to the cumulative transmission range of other cluster heads in the network, substantially more nodes are in the vulnerable region which will severely affect the uplink transmission thus reducing the scalability of the dual hop clustered network. To mitigate the hidden terminal problem posed by the large interference range of the cluster heads transmission, the total channel pool Q_T will be partitioned into two separate non overlapping sub-channel sets for uplink Q_u and backhaul Q_b, i.e., $QUQ_b = Q_T$.

Interference model and channel assignment schemes: A transmission will be blocked or temporarily stopped depending upon the level of signal to interference noise ratio (SINR) not being below than SINR threshold at cluster head node h_i. All the nodes will have access to the channels via the Distributed Channel Assignment scheme (DCA)[10] and hand shaking protocol will be implemented to eliminate the presence of hidden node terminal problem within a cluster. To negate the exposed node terminal problem which would result in a channel being underutilized and reduce spatial reuse, the cluster heads will only respond to RTS packet of its respective cluster members. Fig. 3 illustrates the flow chart in which a channel is accessed via DCA between cluster member $n_{i\text{-}j}$ and cluster head h_i and the conditions of which a transmission can either be blocked or temporarily stopped.

For comparison purposes, assigning uplink channel Q_u with the highest SINR as employed by Akerberg and Brouwer[11] will also be implemented. Upon receiving RTS from its respective $n_{i\text{-}j}$, h_i will sense all the Qu and assign a channel with the highest SINR to $n_{i\text{-}j}$ for transmission. However, the need to sense all the available Q_u increases the communication overhead and processing requirement compared to that of DCA.

Linkage to system mapping and traffic modeling: Truncated Shannon Bound (TSB) is adopted to map the signal to interference plus noise ratio (SINR) level to capacity[12]. The TSB describes the relationship between SNIR and bandwidth efficiency of different modulation scheme. According to the TSB the, achievable channel capacity for a user can be obtained by:

$$\text{Channel capacity}\, C_{TSB}, \frac{\text{bps}}{\text{Hz}} = \begin{cases} C_{TSB} = 0 & \text{for SINR} < \text{SINR}_{\min} \\ C_{TSB} = \alpha B\,(1+\log_2 \text{SINR}) & \text{for SINR}_{\min} < \text{SINR} < \text{SINR}_{\max} \\ C_{TSB} = BC_{\max} & \text{for SINR} > \text{SINR}_{\max} \end{cases}$$

Where, α is the attenuation factor, B is the channel bandwidth, C_{TSB} is the channel capacity, $SINR_{min}$ is the minimum SINR at which a signal can still be successfully received by a receiver. The parameters of the TSB are $\alpha = 0.65$, $SINR_{min} = 1.8$ dB, $SINR_{max} = 21$ dB and $C_{max} = 4.5$ bps Hz^{-1}.

A poisson traffic model was used to access and evaluate the performance of the dual hop clustered networks and the file lengths are fixed at 45 Mbs.

Energy consumption model: Although the researchers noted that a node has to remain awake or idle, it is assumed that energy is only consumed during transmission and reception only[5]. Such assumptions however may not be applicable to higher powered devices such as network interface for IEEE 802.11b as the energy consumed during idle period is comparable to that during reception[13,14]. Unlike the energy consumption model by Heinzelman *et al.*[5], the energy consumed by a node during transmission e_t and reception e_r as presented in Eq. 4 and 5, respectively, will be affected by the external radio environment i.e., interference since the period in which a node spends time for transmission or reception t_s of a file/data is dependent upon the file length f_h and the channel capacity which is mapped to SINR:

$$e_t = t_s.Pt_{ni} \qquad (4)$$

$$e_r = t_s.p_e \qquad (5)$$

where, Pt_{ni} is the required transmitted power such that the receiver can successfully receive the transmission and is dependent upon the required radiated transmitted power Pd_{ni}, Pt_{ni} remains constant upon concurrent transmission and reception by a cluster head as unlike macro base station in which the power consumption scales with the number of connected users in a given time, the affect is negligible in smaller cells[15] and p_e is the power consumed by all the electronic components in a wireless network interface card and thus it is also the power consumed during idle mode.

As by Heinzelman *et al.*[5], it is assumed that there is a linear relationship between transmitted power consumption Pt_{ni} and the required transmitted uplink radiated power. The measurements conducted by Ebert *et al.*[16] on commercially available IEEE 802.11 wireless network card as presented in Fig. 4 is used to map the relationship between and Pt_{ni}:

$$Pt_{xi} = 9.Pd_{ni} + p_e \qquad (6)$$

Power savings can be achieved by effectively turning off or forcing nodes into sleep mode when they are not transmitting or relaying files from their neighbors. Sleep

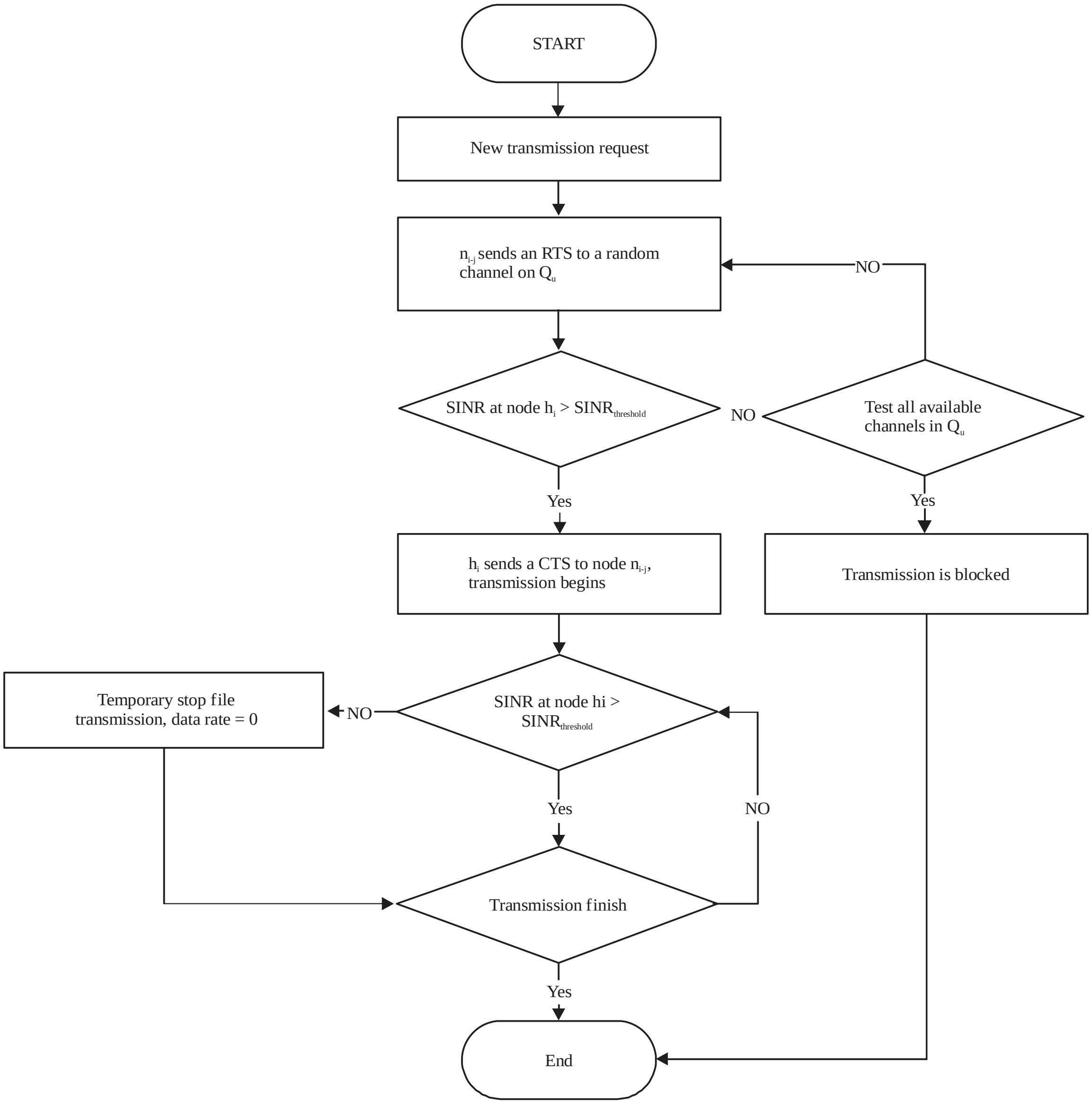

Fig. 3: Flow chart of channel access and the conditions in which transmission is either blocked or temporarily dropped

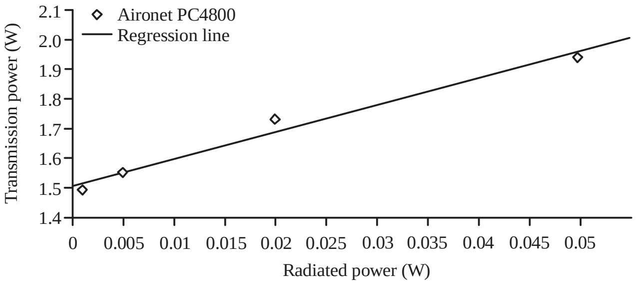

Fig. 4: Relationship between transmission power consumption of IEEE 802.11 and the actual radiated power

mode can consume up to 100 times less energy than transmission mode it is therefore considered negligible[17].

Therefore, a comparison is made on the dual hop clustered network energy efficiency between when the nodes in the network are in idle mode when it is not transmitting or receiving with that when the nodes conserve energy by going into sleep mode when it is not required to transmit or receive a file. Such an energy saving technique however assumes an ideal scenario as it would require the cluster heads to accurately predict and anticipate the occurrence of uplink transmissions such that it can serve its respective cluster members.

RESULTS AND DISCUSSION

A file based traffic model was adopted, assuming a negative exponential inter-arrival time, with a fixed file sizes. The end-to-end system throughput is a summation of the throughput all users within the system, taking into account constraints (bottlenecks) within both the access and backhaul segments. In the case of the single hop, the system throughput relates to just the throughput of the access network. In the clustered network all the simulations were conducted during the steady state phase i.e., all the clusters in the network has been formed and with geographical distribution of cluster heads and cluster members generated followed that of the sumRSSI clustering algorithm[7]. Monte-Carlo simulation technique is applied to evaluate the performances of the networks. The values of the parameters used are summarized in Table 1.

Varying offered traffic: To study the energy efficiency, it is crucial to understand how the system throughput varies with offered traffic. Figure 5 illustrates a single hop and the dual hop clustered network (denoted as C_n) throughput with random channel scheme denoted as DCA and highest SINR scheme. The transmission range r of a cluster is set at 250 m which corresponds to an average of 7 clusters generated via sumRSSI clustering scheme. The channels for the uplink Q_u and backhaul Q_b are split equally from Q_T i.e., $Q_u = Q_b = 20$.

The saturation of throughput for the cluster as presented in Fig. 5 is caused by not only the bottlenecks on the backhaul segment due to high traffic load and limited availability of Q_b but also due to the high rate of files transmission being stopped due to high interference at the cluster head. This causes the actual throughput of the dual hop clustered network to be lower than that predicted by Eq. 2. The high interference is induced by overlapping clusters and the hidden node terminal problem; the effects are reduced by assigning channel with the highest SINR. However, as mentioned earlier, highest SINR scheme requires greater communication and processing overhead.

The relatively high interference means that the DCA scheme also suffers from additional delay per file to the cluster head than highest SINR as illustrated in Fig. 6. At high offered traffic levels, the end to end delay is caused primarily by files being buffered in the cluster heads as Q_b is too congested.

Table 1: Summary of system parameters

Parameters	value
Size of network layout	1,000×1,000 m
Number of nodes	100
Centre frequency	2.1 GHz
Carrier bandwidth	1MHz
Maximum radiated transmit power	0dBW
Node Antenna Gain (Gt,Gr)	0dBi
Noise figure	5 dB
SINRthreshold	5 dB
SNIRmax	21 dB
Noise floor	-134dBW
File length f_h	45Mb
Nodes antenna heights	25 m
Cmax	4.5bps/Hz
The total number of available channels QT	40
Traffic model	Poisson

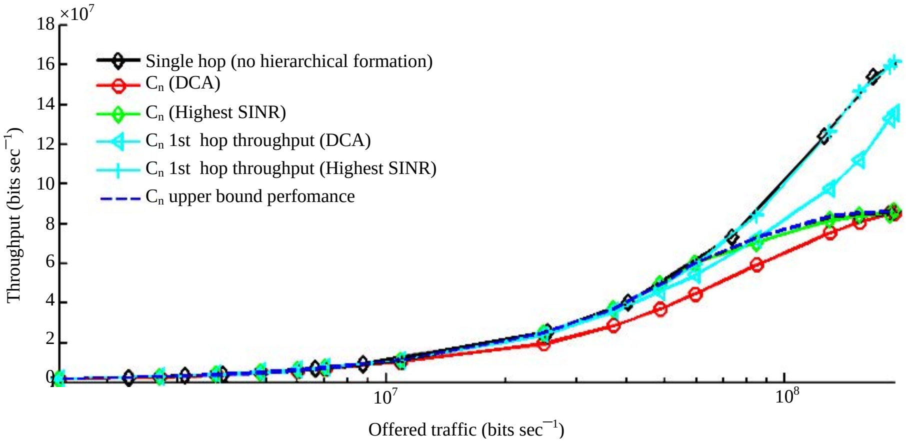

Fig. 5: Dual hop clustered network throughput performance against various offered traffic levels

The Energy Consumption Rating (ECR) metric which was employed by Han *et al.*[18] is used to gauge the energy efficiency of the networks as it takes into account not only the energy consumed but also the throughput. Figure 7 illustrates the ECR in joule per bit of a single hop network and clustered networks with random channel assignment (DCA) and highest SINR schemes. The clustered networks are treated with an ideal energy saving scheme (cluster heads are assumed to be in sleep mode when it is not transmitting and/or receiving) denoted as ES and without energy saving (cluster heads continuously stay in 'Active mode'). Figure 7 also shows the power consumed for three different p_e levels in order understand how the energy efficiency of clustered networks are affected by proportion of energy consumed during transmission, reception and idle period. The result for when p_e is zero, shows the energy efficiency of clustered networks when transmission power consumption Pt_{ni} is the dominating factor.

The results for Energy Reduction Gain (ERG) are presented in Fig. 8 for each p_e level in order to quantify the amount of increase in energy efficiency for dual hop clustered networks via a more interference resistance channel assignments (between DCA and highest SINR) and the application of an efficient energy saving scheme.

Fig. 6: Average normalized delay per file for various offered traffic levels

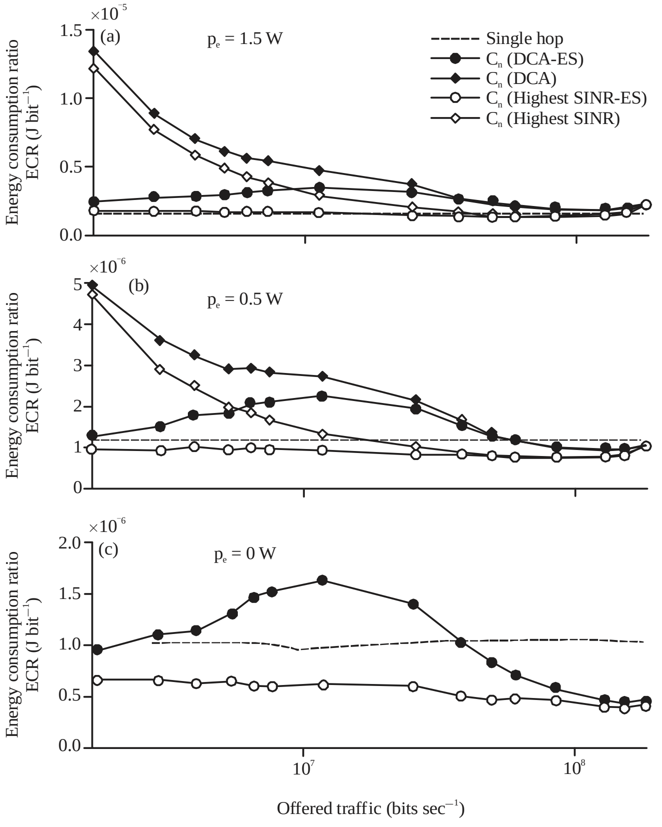

Fig. 7(a-c): Energy efficiency (ECR) of clustered network against various offered traffic and p_e

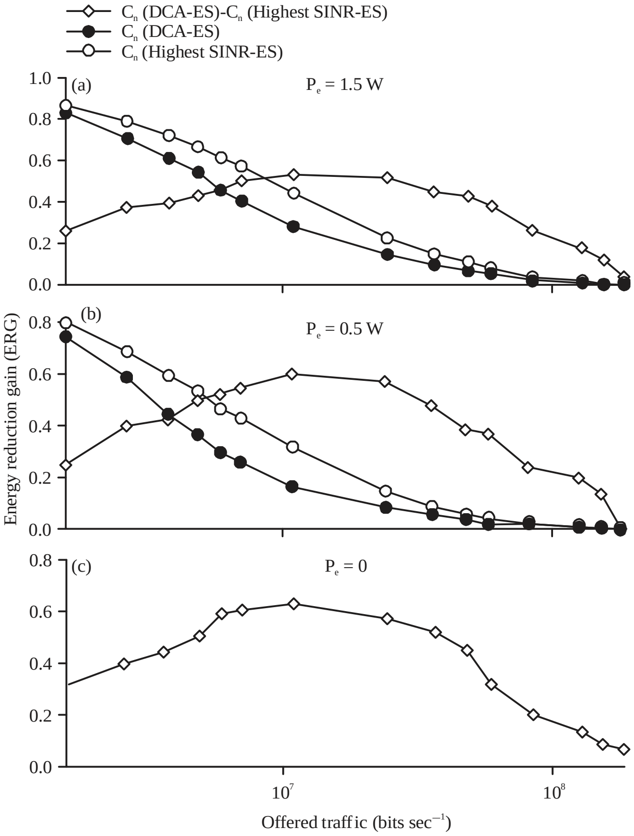

Fig. 8(a-c): Energy reduction that can be gained via energy saving scheme and interference reduction in dual hop clustered networks for various offered traffic and p_e

The results of ECR and ERG illustrate that applying energy saving scheme can theoretically improve the clustered networks energy efficiency by more than 80% compared to when there is no energy saving scheme. The efficiency progressively reduces to zero at higher offered traffic loads as more files has to be relayed thus nodes have to remain on for longer periods of time. Under a real world scenario, the energy saving scheme cannot obtain this Fig. 8 as it would require perfect anticipation of cluster heads to be turned on to serve its cluster members. A delay in the rate of cluster heads turning on would result in a data loss and thus reduce the throughput or would require the respective cluster member to transmit to neighbouring cluster heads that is in idle mode or to HBS directly which would increase the transmission power by the node due to greater transmission distance. Comparing highest SINR-ES and DCA-ES indicates that the energy efficiency of dual hop clustered network is susceptible to intra-cluster interference as high interference causes the uplink channel capacity to degrade which increases the end to end delay. Reducing end to end delay through efficient channel allocation can improve the energy efficiency of the network by 50%.

Based on the results of ECR at $p_e = 0$ W and $p_e = 0.5$ W, the energy efficiency of a dual hop clustered network has the potential to be more energy efficient than a direct single hop transmission provided that the energy consumed by cluster heads during idle and receive mode cluster heads are turned off when there are no uplink transmissions to be relayed and that the interference is minimized.

Uplink and backhaul channel allocations: To understand how the proportioned allocation of available channels Q_T between the Q_u and Q_b affects the performance and energy consumption of clustered network, a Monte-Carlo simulations was performed by varying the ratio of Q_u and Q_b with the energy model under the best case scenario i.e., cluster heads are turned off when they are not relaying files to the HBS and $p_e = 1.5$ W.

Figure 9 illustrates that the throughput at an offered traffic level of 2 Mbs is identical to the upper bound performance predicted in Eq. 2 as it does not suffer from any channel contention and dropping throughout Q_u/Q. As mentioned earlier, the throughput of C_n is impaired by mainly the bottleneck on the backhaul segment as can be seen when

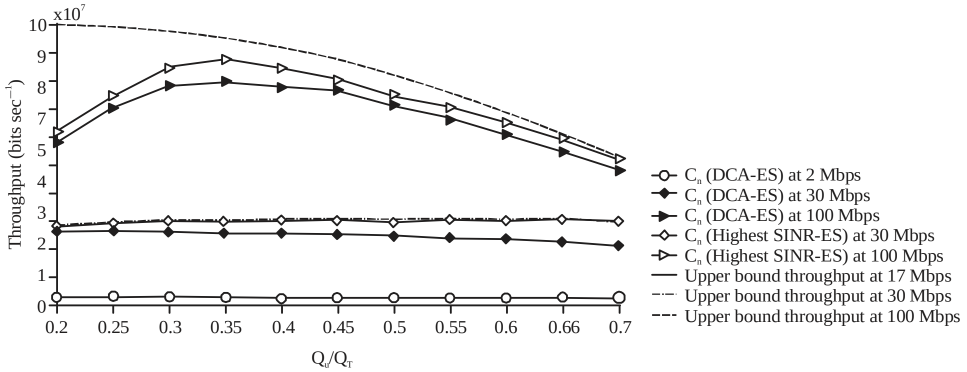

Fig. 9: Throughput of dual hop clustered networks with varying uplinks to backhaul channels allocation (with $p_e = 1.5$ W)

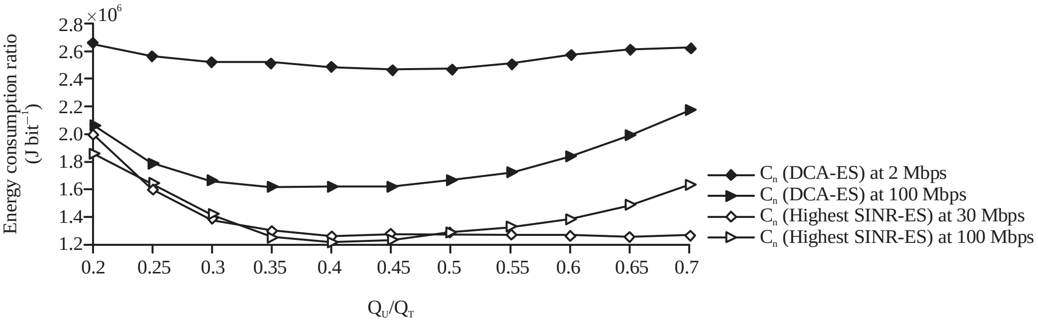

Fig. 10: Energy efficiency of clustered networks against various uplinks to backhaul channels allocation (with $p_e = 1.5$ W)

more channels are allocated to the uplink Q_u the throughput deteriorates. However, at an offered traffic level of 100 Mbs, the inadequate Q_u causes deterioration in the throughput and the dual hop clustered network performance is optimised when 60% of the channels are allocated to Q_b.

The energy efficiency of C_n at different uplink to backhaul channel ratios is shown in Fig. 10. Although in general the throughput decreases with increase in Q_u/Q, at an offered traffic of 30 Mbs for C_n (Highest SINR), the network becomes more energy efficient with having more channels allocated to the uplink. This reduces the channel contentions which in turn means nodes are in transmission mode for a shorter duration hence consumes less energy. When a transmission is blocked, it is assumed that the node is turned off. The architecture appears to be most energy efficient when Q_u/Q_s between 0.4-0.5.

Energy efficiency for various numbers of clusters: The transmission range r in which cluster heads announce their existence affects the number of clusters formed in the network[19]. Figure 11 illustrates the energy efficiency of dual hop clustered network ranges from 2-13 by varying transmission range r for the cluster scheme sumRSSI with pe = 0.5 W and $Q_u = Q_b = 20$.

It is suggested that the upper bound cluster transmission range should not exceed //3 in order to minimize dropping/interruption of file transmissions[7]. This claim is supported by the findings in this paper as demonstrated in Fig. 12 in which the relatively high offered traffic causes the throughput to drop as the number of cluster decreases. However based on the result shown Fig. 11, the numbers of clusters affects the energy efficiency dual hop clustered network in different ways depending upon the offered traffic.

At relatively low channel contention i.e., when C_n (DCA) and C_n (Highest SINR) is at an offered traffic of 30 Mbs and 50 Mbs, respectively, the clustered network is most energy efficient when the cluster transmission range is in the order of 0.5 to 0.55 of network area which corresponds to 4-5 clusters. The result for low channel contention amongst clusters is in line with the analysis provided by Heinzelman *et al.*[5] which assumes that the channel capacity and hence transmission delay remain unaffected due to interference. Heinzelman *et al.*[5] suggested an optimum number of cluster lies around 3-5.

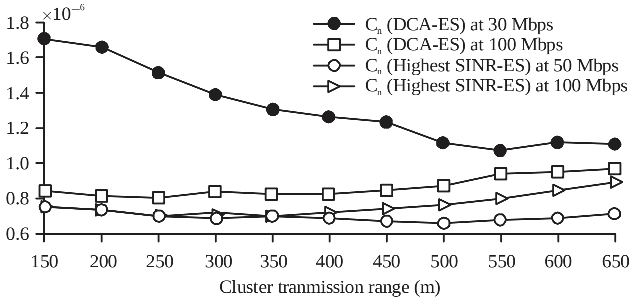

Fig. 11: Energy efficiency of a dual hop clustered network for various number of clusters (with $p_e = 0.5$ W)

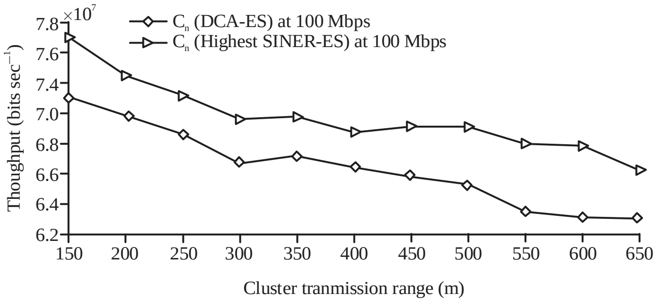

Fig. 12: Throughput of dual hop clustered network under high uplink channel contentions for various number of clusters (with $p_e = 0.5$ W)

For a high offered traffic level e.g., at 100 Mbs, the energy efficiency of the dual hop clustered network is at an optimum when there are around 6-9 clusters. The discrepancy between the optimum numbers of clusters for the high and low offered traffic is due to the channel contention amongst transmitting nodes. At high offered traffic where there are more concurrent uplink transmissions, the shortage of uplink channels Q_u, requires the channels to be re-use more regularly by nodes in the network. The addition of delay coupled with the high total power consumption by cluster members due to large transmission link length of resulted in the energy efficiency to decrease with fewer clusters.

Based on the results presented, energy efficiency of clustered network can theoretically be improved by more than 80% when an energy saving scheme is applied in a clustered network. The general trend is that the lower the offer traffic level, fewer clusters are needed in order to maintain certain QOS. A predictive energy saving technique can be applied to cluster heads such as that proposed by Li *et al.*[20] in which under low traffic loads, some cluster heads are forced into sleep mode and will 'Wake up' based on its prediction regarding the future traffic load on a certain time.

CONCLUSION

The simulation results illustrate that reducing the end to end transmission delay via an interference mitigating channel assignment scheme can provide improvement up to 50% in the global energy efficiency of a clustered networks. The interference can also be reduced by a having well distributed and compact clusters as it minimizes the radiating interference to neighboring clusters.

The dual hop clustered networks can only become more energy efficient than the standard single hop if the transmission power dominates the total consumed power of devices coupled with interference mitigating channel assignments schemes and power saving scheme.

The efficiency can be further optimized by allowing cluster heads to be in sleep mode when it is not needed to relay files and by splitting the total channels $Q_u/Q_T = 0.4$.

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