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Low Power Routing and Channel Allocation of Wireless Video Sensor Networks Using Wireless Link Utilization

HYUNG-WON KIM* AND AMIT KACHROO

*Department of Electronics Engineering,
Chungbuk National University, Cheongju 362–763, South Korea*

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This paper analyzes the physical relation between the power consumption and the link utilization of wireless video sensor networks. It then proposes a method of multi-channel allocation and routing for multi-hop wireless sensor networks where each node is a battery-powered video camera sensor. Battery powered video camera sensors are often used in a form of a wireless mesh network to cover a large area. We analyze the power consumption model for a wireless link in terms of the distance and its utilization ratio. We present a formula of routing and channel allocation using only active sensor nodes in a way that minimizes the overall power consumption while ensuring transmission of the target video data. We developed a fast heuristic algorithm, and implemented it in a wireless video sensor network simulator. It introduces a notion of aggressor and victims of shared channels to calculate utilization incrementally as the routing algorithm proceeds. Extensive simulation results are provided with wireless video sensor networks of various sizes, which show the performance advantage of the proposed algorithm.

Keywords: Wireless sensor network, mesh network routing, multiple channel allocation, video sensor network, link utilization, low power network.

I INTRODUCTION

As the security requirements are ever increasing in recent years, the demand for security or surveillance camera sensors are rising in many applications. Recently wireless video cameras on battery power are increasingly deployed

*Corresponding author: Tel.: +82–10-9660–6110; hwkim@cbnu.ac.kr

to cover large areas, where power lines or Internet are not available. The power source for battery recharging, however, is often limited, and thus conserving the battery power is the most important issue in such wireless video sensor networks [16][17][18][19] [20]. A wireless video sensor network (WVSN) is an extended type of wireless sensor networks (WSN).

A. Background

In the past, much of research has been done in the areas of WSNs. It is, however, relatively recent that WVSN has received a lot of attention. WSNs are generally assumed to carry sensor data of very low bit rate, while WVSNs usually transfer video data that is high bit rate and often real time. The goal of most WSN is to maximize the life-time of the network, or to reduce the data delivery time. Such goal becomes more challenging for WVSN due to the network properties of high data rate and real time delivery.

Most of today's commercial wireless cameras use wireless networks based on Wi-Fi (IEEE802.11 standards) with an access point system operating in the infrastructure mode [7][9]. However, such wireless networks have many restrictions in their data rate, wireless range, traffic congestion, and also battery lifetime.

A wireless mesh network can provide a promising solution to these problems, where each camera sensor operates as a node in a mesh network. Multi-channel routing schemes can be used to reduce the RF interference and traffic congestion, and to enhance the video data rate while minimizing the power consumption [4][5][6][7].

B. Related work

Wireless mesh networks are the emerging solutions for wireless video sensors due to their low cost deployment, robustness and performance .In past, a lot of research has been published in this domain. This has increased the understanding of the design and deployment of such networks.

However, most of this research has been done considering one characteristic of the wireless network into considerations such as data reduction, power control, channel assignment, routing or topology control etc. In practical scenario's, these individual considerations are not feasible for the overall performance of the wireless video sensor networks utilizing mesh networks for their functionality. These objectives also vary from one application to another. To understand the background of our work, we need to understand each and every important individual major objective with the related work.

The first objective is to minimize the camera data size to transfer through the WVSNs [4][5][6][7]. Prior techniques also have attempted to reduce the energy consumption by selecting or combining overlapped field of views (FoVs) if such overlapped images are available by multiple camera sensors [11][12][13][14][15][16].

The second objective is power control that is assigning transmission power level to video sensor nodes so that they have minimum interference and better throughput. This is a very popular domain for wireless researchers and there are numerous research publications in this area. In [28], authors stress upon the uniform power control in ad-hoc network and present the architecture, theory and implementation of their protocol –COMPOW. However, as the scale of networks grows, a uniform power control is not effective for maximum throughput and reliable wireless video sensor network. In [29], authors have presented the case of variable power control for topology control. In our scenario, we utilize variable transmission power based on the distance for best throughput.

The third objective is channel assignment. It deals with assignment of channels to each link of a wireless sensor network. The main aim of channel assignment is to limit interference from the same frequency channel and increase overall throughput of the network. Authors in [30], present the motivations and challenges in multi-channel multi-radio mesh networks. In [31], an interference aware channel assignment in multi radio mesh networks in presented by using graphs.

The fourth and final one is routing. Routing in wireless video sensor networks is to choose routing paths so as to satisfy the end-to-end traffic demands between nodes. The routes should have low interferences and should have high reliability and throughput. In [32], authors have presented their routing mechanism in multi-channel multi-hop wireless networks with single interface. In [33], the authors have analyzed the effect of straight line routing in large multi hop wireless networks.

In real scenarios, we can't assume that by optimizing a single individual characteristic will improve the overall performance of the network and this becomes clear in real life deployments and experiments on test beds. Considering real life deployment and simulation of practical scenarios, there is a need for joint optimization of various individual characteristics of wireless mesh network. A lot of recent research publication stress upon these joint optimization characteristics. Some of the famous contributions in this field are [34]: power control and scheduling, [35][36]: routing and scheduling, [37]: routing and channel assignment, [38]: routing, scheduling and channel assignment, [39]: routing, scheduling and power control.

Our work is a joint optimization of power, channel assignment, and routing based on link utilization parameters. It closely resembles the work in [40] but the difference lies in our use of the relation of transmit power and data utilization.

C. Motivation

In this paper, we propose a new method of multi-channel allocation and routing selection for WVSNs,where each node has an event-driven camera sensor. Here the camera sensorcaptures video for a short period of time only when it detects a motion or sound; the camera sensor stays dormant otherwise. We show simulation results that prove that the method can minimize the power of a wireless mesh network of video sensor nodes. It also ensures thatall the routing paths have enough data rate to carry al video data from all the camera nodes.

Often camera sensors are battery powered, and so it is required to minimize the energy consumption. It is also required to deliver the captured video streams to a sink nodein a real time fashion [10][12][13][14][15]. Radios of multiple channelsare often adopted in wireless sensor network, since using multiple channels simultaneously allows concurrent transmission and thus increase the overall data rate. It has been proven, however, that the multichannel allocation and routing problem is NP-hard [5]. In the mesh network of our concern, each node generates intermittent video data (driven by events). Only the nodes currently transmitting data are active while all others are in sleep mode. New constraints are added to minimize the energy consumption. Event-driven video data is delivered through active-mode nodes avoiding sleep-mode nodes whenever possible.[21][22][23][24][25].

In general wireless networks, the dominant component of the power consumption is the transmit power of each wireless link. Most of prior work, however, proposed routing and channel allocation methods assuming each node uses the same TX (transmit) Power and the same data rate regardless of the actual transmission distance to the next destination nodes [4][5][6][7][8][9]. While this assumption allows simpler optimization formula, it often leads to results drastically different from realistic power consumption. In reality, path loss increases exponentially along with the distance, and so requiring TX power increase to keep up with the data rate. The general form of path loss in free space is given below:

$$\textit{Free space path loss} = \left(\frac{4\pi D}{\lambda}\right)^{\gamma}$$

Here, D is the distance, λ is the wavelength of light, and γ is path loss exponent, which is 2 for the ideal free space, but is usually 3~4 depending on the medium condition. In general, since TX power cannot be increased infinitely to recover the path loss, wireless modems usually lower their MCS (modulation and code scheme) -- in other words lowering the data rate -- as the transmit distance increases [1][2][3][26].

In this paper, we propose a routing method for WVSNs taking into account realistic link data rates and TX power as a function of the distance between nodes. Our network topology is a mesh network that has one sink (destination) node and a large number of sensor nodes transmitting video data towards the sink. To conserve battery power, only the nodes with captured data wake up and form a mesh network topology, while other nodes are in the sleep mode. We introduce a concept of link utilization ratio, which is a succinct but realistic method of calculating TX Power. If a routing path from a node changes, the link utilization of all links along the path also changes. This is because the amount of transferred data changes along the path, and the data rate of each link changes. Therefore our goal is to find the best routing paths from all active nodes towards the sink in a way that minimizes the sum of TX power while ensuring the selected paths provide enough link utilization to transfer all the video data. We also allocate a different RF channel to each link within the interference range, so multiple nodes within the wireless range can transmit data simultaneously. This way, we can ensure the real time delivery of a large amount of video data from all the active nodes.

To the best of author's knowledge, no previous work provides a similar solution to our proposed method. Most of previous work either provides routing solutions assuming the TX power from all nodes is constant, or finds routing paths using only 1 RF channel. Therefore, most of the previous work is suited for low data rate sensor networks, while our method is well suited for high rate video sensor networks with real time delivery.

In Sec. II, we introduce a new approach to wireless video sensor network modeling, which employs link utilization and channel utilization calculation. Sec. III presents formulation of optimal routing and channel allocation followed by an efficient heuristic algorithm with examples. We then provide an extensive set of simulation results in Sec. IV, and conclusions in Sec. V.

II WIRELESS VIDEO SENSOR NETWORK MODELING

A. Wireless Network Topology and Assumptions

In general, battery powered video camera sensors wake up and transmit video data, only when events are detected, while they are placed in their sleep mode for other time. A wireless video sensor network covers a large area but it has only one or a few data collection gateway nodes, which collect all video data and send it to a data center by a wire-line internet.

In this paper, we assume that in a wireless video sensor network, only a subset of the nodes wake up during a short period of time, and then go back to sleep mode after data transmission. We assume there is only one data collection gateway node, which we call a sink node s. Each active node transmits video data towards the sink node via multi-hop routes.

Each node has multiple IEEE 802.11n (Wi-Fi) modem and transceiver that can connect to multiple neighboring nodes using different channels. Each wireless link between two nodes is called an edge e. Each edge uses one Wi-Fi modem with one channel.

Fig. 1 (a) shows an example deployment of wireless sensor nodes, where 100 nodes are uniformly installed in a 10×10 area. Fig. 1 (b) shows a case when only 9 nodes of them are active for a given time duration. Each active node generates its own video data and transmits towards the sink node 'S'

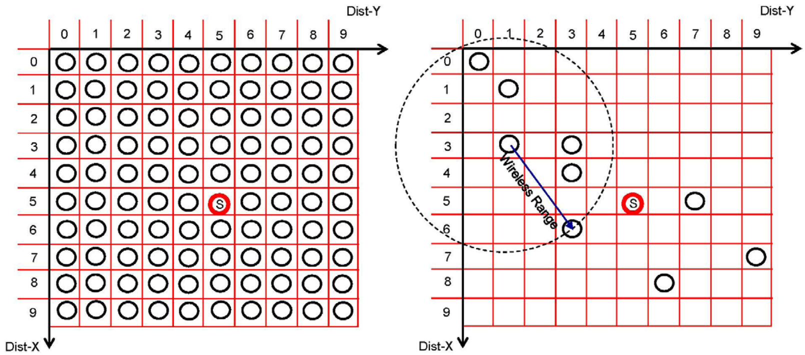

FIGURE 1
Example deployment of wireless video sensor network: (a)All 100 nodes are presented by circles with the sink node by 'S'; (b) Active 10 nodes are presented by circles while sleeping nodes are deleted from the network.

(red circle) through neighboring nodes within its wireless range. The wireless range of some nodeis indicated by a dotted circle.

Fig. 2 shows an example network topology of the proposed method, which is composed of potential edges between nodes in their wireless ranges. Our routing algorithm selects a set of active edges from Fig. 2 in a way that the selected edges construct multi-hop paths from every active node to the sink. These paths should deliver all video data to the sink with minimal power consumption.

In summary, the WVSN that is considered in this paper has the following properties:

Properties of the Wireless Video Sensor Networks Considered:

- The nodes are deployed randomly in square area.
- All nodes have video sensors with event sensing capabilities.
- Each node wakes up on an event, and transmits captured video, then goes back to sleep mode after the event disappears.
- Each node encodes the video data and transmits the compressed data.
- The wireless network topology is a mesh topology consisting of only the active nodes
- The nodes are stationary and the communication between the nodes is unaffected by fading
- Each node can communicate to its neighbor nodes within its wireless range, and to all active nodes via multi-hops
- The nodes whose status changes (active or sleep) report the status to their neighborsand the sink node.
- The sink node conducts centralized routing and channel allocation,and updates the results to the nodes whose route and channel have changed.

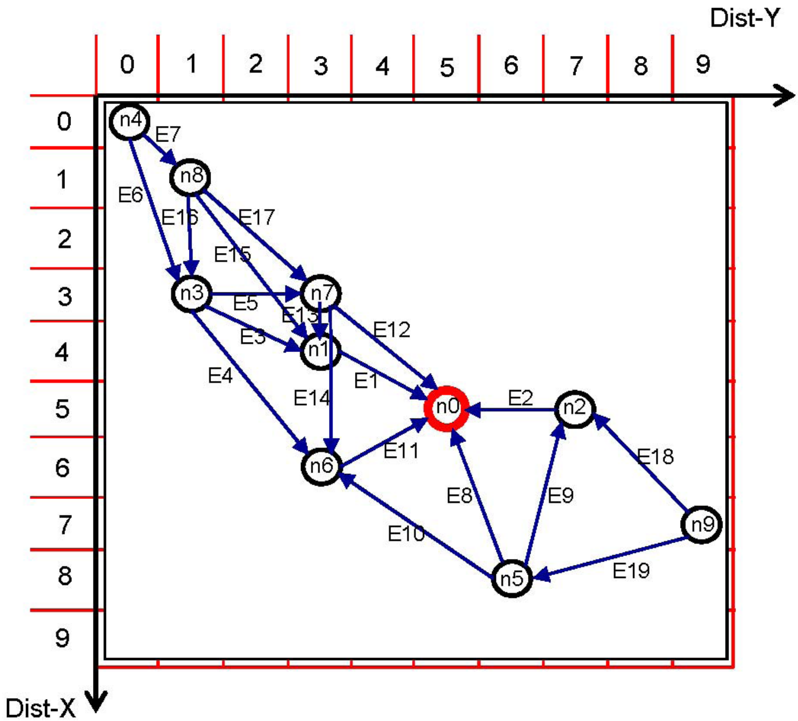

FIGURE 2
A mesh network topology formed by the active nodes of the WVSN example of Fig. 1. The edges in the network indicate all potential connections between two active nodes within their wireless ranges.

- Every node is equipped with multiple 802.11n Wi-Fi radio interfaces, so each wireless link on this node can be assigned with a different channel.
- The distance of each wireless link determines its TX power and modulation scheme using apower-modulation table, which is preconfigured empirically for the best data rate.

In this paper, we use IEEE 802.11n with 5 GHz spectrum, and we use 36 non-overlapped channels of 20MHz channel bandwidth. For a two stream Wi-Fi modem configuration (2x2 MIMO), the maximum physical layer data rate is 150Mbps. Based on the measured results with commercial Wi-Fi modules, we take 30% off for MAC and IP layer overhead. We therefore assume that the maximum link rate of each edge is 100Mbps.

Since a Wi-Fi modem, like other wireless technologies, can interfere with others if operated in the same RF channel. Therefore, we allocate different channels to edges within the same wireless range, if possible. To allow each node to transmit and receive simultaneous from/to multiple nodes, we installmultiple Wi-Fi radio interfaceson each node. Fig.3 (a) illustrates an

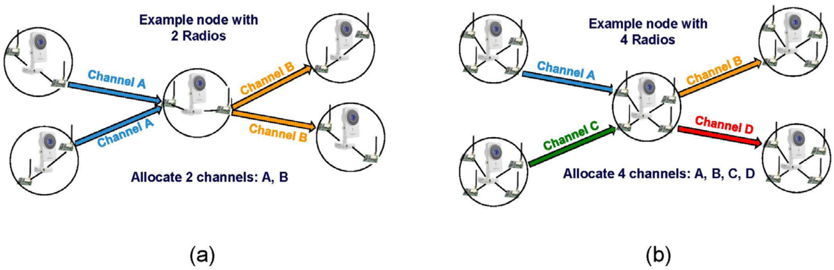

FIGURE 3
Example nodes with multiple WiFi radios for simultaneous receive and transmit of data: (a) A node with 2 radios but has 4 links. 1 radio is shared by 2 receive links, and 1 radio is shared for 2 transmit links; 2 channels are allocated; (b)A node with 4 radios. Here each radio can be allocated to the individual 4 links with 4 different channel.4 channels are allocated.

example node with 2 Wi-Fi radios installed. If the router allocates 4 links to this node as in Fig.3(a), 2 ingress links can share one radio, and 2 egress links can share the other radio. In this case, we allocate 2 channels A, B, so we allow 2 simultaneous transmissions. This node can provide 2 times higher throughput than a node with single radio. Fig.3(b) shows an example node with 4 Wi-Fi radios installed. If the router allocates 4 links as in Fig.3(b), all 4 links can have individual radio with different channels. This node can provide 4 times higher throughput than a single radio node. Here the 4 edgeson the node can have 4 different channels and so they allow simultaneous transmission.

Fig.4 gives an example wireless video sensor network where all edges can transfer data simultaneously. All edges of the network are covered with 6 channels. Each edge from any node is allocated with different channels (indicated with different colors). Each node's data is transferred towards the sink node, which is a gateway access point with a wire-line connection to the Internet.In this paper, we assume that a regular node has at least 4 Wi-Fi radios. On the other hand the sink node, which is AC-powered, has a large number of Wi-Fi radios to receive a large number of links.

B. Link Utilization Analysis and Power Model

We formulate the problem of finding channel allocation and routing in a way to minimize the total TX power. While sleep-mode links have no TX power, active-mode links consume TX power only during they transmit actual data. Hence we calculate the time duration of data transmission by deriving a link utilization rate from a maximum link rate and the total amount of current data rate on each link.

We then propose a fast heuristic algorithm that finds a low power routing solution while ensuring delivery of all video data through multi-hop routes. This way, the proposed method ensures each sensor node's maximal battery life, and avoids data congestion in the sensor network.

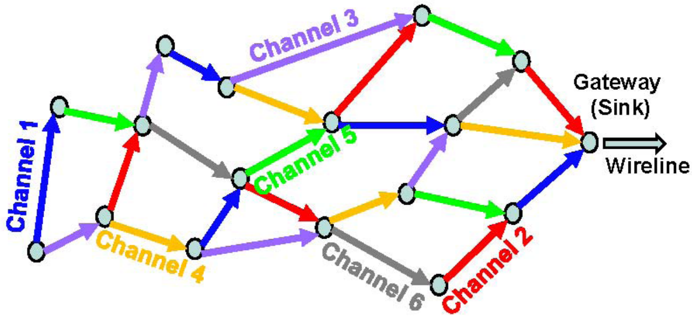

FIGURE 4
Example active nodes with multi-radios and wireless links connecting the nodes using different channels.

We implemented the proposed routing and channel allocation algorithm in a C program (WiSeR) with network models based on IEEE 802.11n. We present simulation data, which show that the proposed method gives routing results with lower power compared to conventional routing algorithm.

Each edge's link rate varies depending on the distance between two nodes, and on the radio channel condition. From the measurement of wireless modem modules, we can observe the following relations.

Let D be the distance from a source node to a destination node. A general formula for the path loss for a wireless link is given by (in unit of dB) :

$$Path\ Loss, L_p = 10\log_{10}\left(\frac{4\pi D}{\lambda}\right)^2 \tag{1}$$

Here λ is wavelength of the RF signal. The TX power $P_{TX}(e)$ for each edge can then be represented as follows (in unit of mW):

$$TX\ Power\ P_{TX}(e) = \frac{10^{L_P}}{10\alpha} \tag{2}$$

Here α is a channel factor. As described above, the maximum link rate is assumed as 100Mbps, which is R_e^{max}. Then with distortion factor β, a possible link rate for each edge e can be defined by

$$Link\ Rate\ R(e) = \frac{R_e^{\max}}{P_{TX}(e)\times\beta} \tag{3}$$

In EQ (2) and (3), α and β are determined impirically from the measurement results of TX power vs. data rate using commercial Wi-Fi modules. From EQ (1), it can be observed that the TX power increases withthe sequare of the distance of the link. Commercially available Wi-Fi modules, however, have limited TXpower range, and we increase $P_{TX}(e)$ at a slower factor and instead lower that modulation scheme to compensate the loss of SNDR (Signal to Noise and Distortion Ratio). The demoninator 10α in EQ (2) reflects the reduced modulation scheme. Moreover, as the TX power increases, the power amplifier of the Wi-Fi modules loses its the linearity and so the error vector magnitude (EVM) of the transmit signal degrades. This effect is modeled by EQ (3), such that the actual link rate rapidly decreases along with increasing TX power. This model gives important contrast to most previous published research, where either the TX power is assumed constant regardless of the distance or the data rate is assumed constant regardless of the TX power value. We conducted measurements of commercial Wi-Fi modules under realistisc experiments to evaluate accuracy of the models. We then observed that such inaccuratesimplistic models of most previous work lead to drastically different data rate and power consumption from the actual measured values.

The user data rate traversing an edge e is defined as $U(e)$. Then the link utilization ratio $UR(e)$ for edge e is defined by

$$Utilization\ Rato\ UR\left(e\right) = \frac{U(e)}{R(e)} \tag{4}$$

Here $R(e)$ is the available link rate for edge $e$given by EQ (3). Since $U(e) \leq R(e)$, $0 \leq UR(e) \leq 1$.

For each edge e, the effective TX power $P_{eff}(e)$ is defined by

$$P_{eff}\left(e\right) = P_{TX}\left(e\right) \times UR\left(e\right) \tag{5}$$

This reflects the important condition that each wireless radio turns on TX power only when its link transmits user data, and otherwise it truns off TX powerand goes into a power saving mode. Hence the total effective power consumption P_{eff}^{net} of the entire network is defined as

$$P_{eff}^{net} = \sum\nolimits_{\forall e} P_{eff}\left(e\right) \tag{6}$$

In this paper, we assume TX power dominates the overall power consumption of active sensor node, and so we consider only the TX power in EQ (6). However, we can easily extend our power model to include other power drain sources for video encoding, radio's receive signal processing, and embedded processor.

We use the above analytical model for the following routing and allocation algorithm and its simulator.

C. Channel Utilization Analysis

EQ (4) holds when edge e_i has no interference in its wireless range, called vicinity $V(e_i)$. This is the case when e_i is allocated a channel different from all other edges in $V(e_i)$. When e_i shares a channel c_k with other edge e_j, however, the effective link utilization of e_i is increased by the utilization of e_j. This is due to the fact that e_i and e_j compete to use channel c_k in CSMA fashion. From e_i's perpective, e_i is called a victim, while e_j is called an aggressor. The effective link utilization of a victim edge is the sum of the victim's link utilization and all aggressor's link utilization.

Fig 5 illustrates an example network, where the dotted circles indicate the wireless range of aggressor nodes affecting the victim node n_7. Consider a victim edge e_{13} using channel c_4. The aggressors for e_{13} are the edges that interfere with the received signals of e_{13}'s receiver (destination) node n_7. Hence the aggressors are determined by the receiver of the victim link, not the transmitter or the link itself. To determine the aggressors for e_{13}, therefore, we check if n_7 is within the wireless range of the aggressor nodes having the same channel as e_{13}. In Fig. 5, the aggressors of e_{13} are the edges e_3 and e_5 which use channel c_4 and whose wireless ranges enclose the victim node n_7. Note that node e_{13}, on the other hand, is not an aggressor for edges e_3 and e_5, because the wireless range of e_{13} does not enclose e_3's and e_5's receiver nodes n_1 and n_2.

Fig. 6 compares the data transmission of edge e_{13} when there is no aggressor and when there are two aggressors e_3 and e_5. Here we assume the link

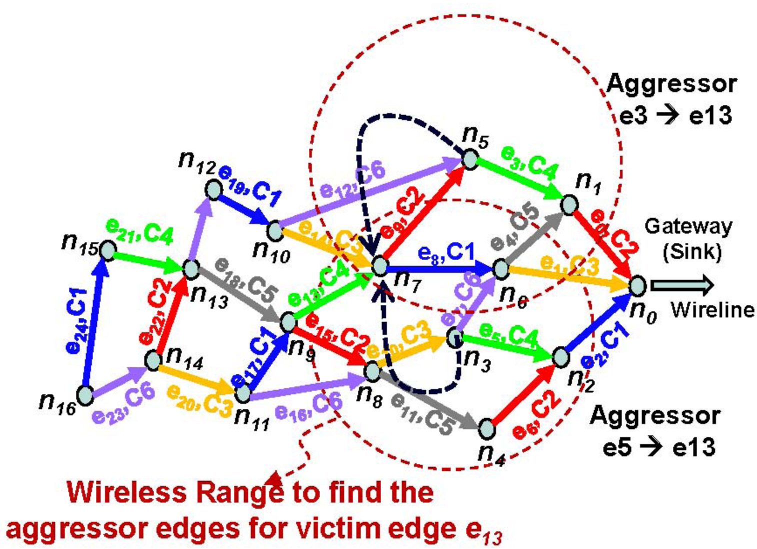

FIGURE 5
Example wireless video sensor network with channel sharing. A victim Edge e_{13} shares Channel C4 with aggressor edge e_3 and e_5.

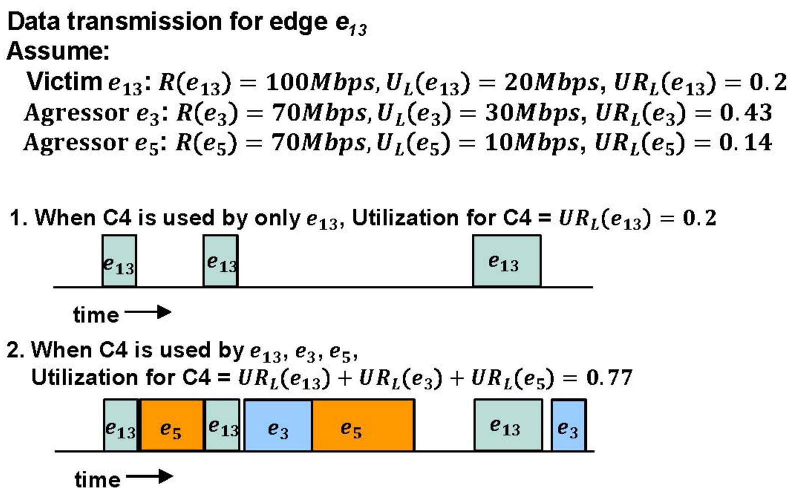

FIGURE 6
Example of a Victim edge and its effective utilization. Data transmission of the victim edge for the case with no aggressors (1) and with 2 aggressors (2).

rates $R(e_i)$ and Utilization $U_L(e_i)$ for the victim and aggressors as indicated in Fig 6. When e_{13} alone uses channel c_4, the effective utilization for c_4 remains unchanged (c_4 is 20% utilizated). On the other hand, when the two aggressor edges share the same channel c_4, the effective utilization for c_4 is the sum of $U_L(e_i)$ of the victim and the two aggressors (c_4 in this case is 77% utilized). The formula of calculating effective utilization $UR_C(e_v)$ of a victim edge e_v for channel c_k is given below.

$$For\ victim e_v, \forall n_a\ whose\ W_a \ni n_v, let\ A_{v,k} = \{e_{a,k}^{egress}\} \tag{7}$$

$$\forall e_{a,k} \in A_{v,k},\ \text{let } UR_C\left(e_v\right) = \sum UR(e_{a,k}) \tag{8}$$

$$UR_C\left(e_v\right) \leq 1 \tag{9}$$

In EQ (7), an aggressor node n_a is a node whose wireless range W_a encloses the victim node n_v. For all such aggressor nodes, let $A_{v,k}$ be a set of their egress edges $e_{a,k}^{egress}$ which use the same channel c_k as victim. EQ (8) defines a channel utilization ratio $UR_c(e_v)$ for the victime_v, where $UR(e_{a,k})$ is the utilization ratio of an aggressor edge $e_{a,k}$. Since the victim edge $e_v \in A_{v,k}$, $\Sigma UR(e_{a,k})$ includes the victim's utilization ratio $UR(e_v)$ as well as all its agressors' utilization ratio. EQ (9) is a contraint that must be satisfied for e_v while the proposed algorithm finds an optimal routing and channel allocation solution, which we describe later.

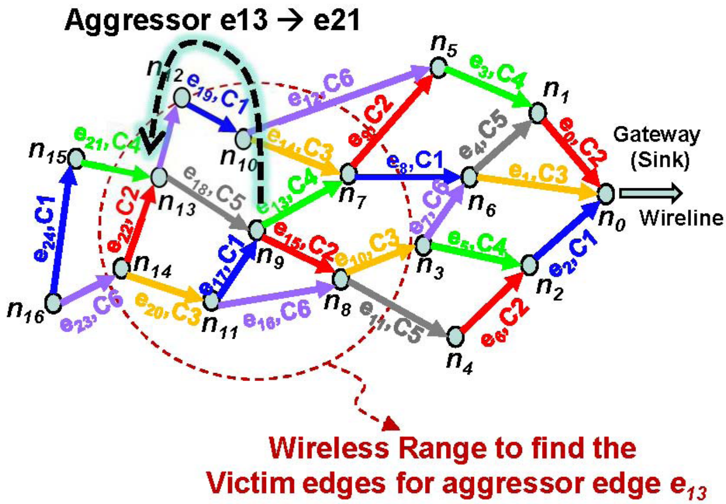

FIGURE 7
Finding victim edges for an aggressor edge in network Fig 6. A agressor edge e_5 affects victim edge e_{13}.

We now consider finding all victims from the perspective of each aggressor, which is opposite to the above procedure finding all aggressors from each victim. For example, Fig. 7 shows how to find the victim edges for an aggressor edge e_5. We use a wireless range for the transmitter node n_6 of e_5 as indicated by dotted circle in Fig. 7. All nodes in this wireless range from n_6 are defined as neighbor nodes of e_5. All the ingress edges to these neighbor nodes that use the same channel as e_5 are the victim edges of e_5. In Fig. 7, e_{13} is the only victim edge for e_5. Whereas finding aggressors for every victim node gives intuitive expression of EQ (7)~(9), finding victims for every aggressor node allows us to implement the proposed heuristic routing algorithm in the same flow as determining each routing path. Both methods lead to the same result though.

III ROUTING AND CHANNEL ALLOCATION

A. Routing and Channel Allocation Formulation

For a wireless video sensor network, suppose ~~only~~ a set N of active nodes n_i have video event and send data to the sink node s. We search for an optimal set E of edges e_i (a wireless link between two nodes). The proposed routing and channel allocation method can be formulated as follows.

Minimize (Objective):

$$\sum\nolimits_{\forall e \in E} P_{TX}\left(e\right) \times UR\left(e\right) \tag{10}$$

for all active edges in E

Such that (constraints):

$$\begin{aligned} &For\ \forall n \in N\ and\ \forall e_i \in Path_{n,s}, \\ &\qquad satisfy\ e_i \in E \end{aligned} \tag{11}$$

$$\begin{aligned} &For\ \forall e_v\ and\ \forall n_a\ such\ that\ n_v \in W_a,\ let\ A_{v,k}\ \{e^{egress}_{a.k}\} \\ &\qquad For\ \forall e_{a,k} \in A_{v,k} \\ &\qquad\qquad satisfy\ UR_c\ (e_v) = \sum UR(e_{a,k}) \leq 1 \end{aligned} \tag{12}$$

Formula (10) is an objective to minimize, where E is a set of all active edges e. If we find a set E in a way that minimizes the sum of $P_{TX}(e) \times UR(e)$ for all e's in E, then E gives an optimal routing for all active nodes.

Formulas (11) and (12) define the constraints that we must satisfy while minimizing the objective (10). Here $Path_{n,s}$ is defined as a multi-hop path from node n to the sink node s. EQ (11) ensures that E contains all the required edges comprising a complete path from n to s. EQ (12) was also defined by EQ (7)~(9), which ensures that the total channel utilization of e_i does not overflow. Here $UR(e)$ in EQ (10) is a link utitlization ratio for all data traffic passing through edge e; on the other hand, $UR_c(e_i)$ is a channel utilization ratio which is the sum of utilization ratios of itself and all its aggressors as defined in EQ (12). If e_i has no agressors in its wireless range W_v, e_i has no channel sharing, and so $UR(e_i) = UR_c(e_i)$. Here, to compute the total power for e_i, we use $UR(e_i)$ not $UR_c(e_i)$, because the TX power of e_i is consumed only when e_i transmits data, not when e_i's aggressors transmit data.

The channel assignment here becomes the problem of coloring the edges of a graph $G(v,e)$, where v are vertices and e are edges, in such a way that no two adjacent edge have the same color. A term known as chromatic index is defined as number of colors required to color the edges of the graph under the condition that no two adjacent edges have the same color. It is well known that finding a chromatic index of any graph is NP complete [41]. So the problem is NP complete. Moreover, when each channel has different cost, it is proven that finding an optimum cost chromatic partition problem is NP-hard [5]. Since the formulation EQ (10)~(12) has additional constraints for finding routing paths in addition to channel assignment, we can deduce that this formulation is also NP-hard. Now that we have proved that finding an optimum solution to the formulation EQ (10) ~ (12) is NP-hard, there is no practical procedure finding an optimum solution. We, therefore, propose a heuristic approximation method to find a near optimal solution in the next section.

B. Routing and Channel Allocation Algorithm

We propose an approximated cost metric $CM_{n,s}^{path}$ and a heuristic algorithm based on $CM_{n,s}^{path}$. This algorithm alleviates the complexity of the optimization formula in III.A.

$$CM_{n,s}^{path} = \sum_{\forall e \in Path_{n,s}} P_{TX}(e) \times UR(e) \tag{13}$$

The proposed heuristic algorithm selects, for each active node n_i, the best edges in a way that minimizes $CM_{n,s}^{path}$. The algorithm starts finding paths for nodes near the sink first, and then paths for nodes farther from the sink. This way it can reuse the cost metric values calculated earlier in the previous paths. Algorithm 1 below describes the main steps of the proposed algorithm.

For each active node n_i, the algorithm forms a graph of edges in E, by searching through all the egress edges from n_i towards sink node $s$and by selecting the edge with the lowest $CM_{n,s}^{path}$. When evaluating each edge, it ensures that the constraints (11) and (12) are satisfied. If any of the constraints cannot be met, it backs off from the selected egress edge, and searches through other egress paths.

Algorithm1: Routing and Channel Allocation Without Channel Sharing

Input: *V = the set of all active nodes, s = sink node, w_i = the wireless range of active node v_i,*

u_i = the bit rate of video sensor of node v_i, c_{max}= the max. number of channels available

Output: *P_{eff}^{net} = Sum of TX power, RouteSet = the set of selected paths, ChannelSet = the set of seleted channels*

Let V_L be a list of $v \in V$ ordered with distance. Let E be the set of all edges. Initialize E = empty.

For $v \in V$ { / Sort the nodes in the order of distance */*

Let $d(v, s)$ be the distance from v to Sink node s.

Add v with the next minimum $d(v, s)$ to V_L.

}

For the next v_i in V_L{ / Calculate utilization ratio of the ordered list of nodes */*

$\{CM_{vi,s}^{path}, path_{i,s}\}$ = ***search_for_route_channel***(v_i)

/ If $CM_{vi,s}^{path} = \infty$, v_i is unroutable, else v_i has a routing $path_{j,s}$ with an effective TX power $CM(e_{i,j})$ */*

if $CM_{vi,s}^{path} \neq \infty$, then $P_{eff}^{net} = P_{eff}^{net} + CM_{vi,s}^{path}$, RouteSet = Insert ($path_{i,s}$), ChannelSet = Insert($c_{i,j}$)

}

search_ route_channel (v_i) {

Let W_i be a set of nodes within the wireless range w_i of v_i

For every $v_j \in W_i$ such that $d(v_i,s) \geq d(v_j,s)$ { / v_i is source, v_j is destination*/*

Let e_{ij} be the directed edge from v_i to v_j; Add $e_{i,j}$ to E

*$c_{i,j}$ = **select_channel** (e_{ij}) /* Select a channel c for e_{ij} such that c is disjoint with all $v_j \in w_i$ */*

if $c_{i,j}$ = NULL, then $CM(e_{is}) = \infty$ and *continue* /* If no disjoint ch. available, jump to next v_j*/

$UR(e_{i,j}) = UR(e_{i,j}) + U(e_{i,j})/R(e_{i,j})$/ Incrementally calculate UR using EQ(3)~(4)*/*

if $UR(e_{i,j}) > 1$, then $CM(e_{is}) = \infty$ and continue / If EQ(12) is not satisfied */*

```
        if v_j ≠ s, /* Recursively call until it reaches Sink*/
            then{CM(e_{j,s}), path_{j,s}} = search_ route_channel (vj)
        CM(e_{i,j}) = P_TX(e_{i,j}) × UR(e_{i,j})/* Calculate the addition of Cost Metric using EQ(2),(5) */
        CM(e_{i,s}) = CM(e_{i,j}) + CM(e_{j,s})/* Incrementally calculate the Cost Metric from v_i to s */
}
    CM^{path}_{vi,s} = MIN [CM(e_{i,s})] /* Find CM(e_{i,j}) of the minimum value */
    path_{i,s} = Insert (e_{i,j} ,path_{j,s}) /* Insert the selected edge e_{j,j} to the end of the path list v_j to s */
    Return (CM^{path}_{vi,s} , path_{i,s})
}
select_channel(e_a) {
    Let n_a be the aggressor node and also the source of e_a
    Let n_v be a victim node within the wireless range w_a of the aggressor n_a
    For eachc_k {/* 0 ≤ c_k < c_max*/
                    c_e = c_k
        For every n_v ∈ W_a
            For everye_v^{ing}/* Let e_v^{ing} be an ingress edge of n_v */
                if c_k is used, then c_e = NULL and break
        if c_e ≠ NULL, then Return (c_e) /* Available channel found */
    }
    Return (NULL) /* No available channel found */
}
```

Since the algorithm finds paths for nodes closer to the sink first, the condition in EQ (12) can be easily calculated by incrementally calculating $UR(e_{a,k})$ in EQ (12) for new edges with prior values of edges that have been already chosen. This is an important property of the proposed algorithm, which allows its rapid routing speed.

C. Routing Example with No Channel Sharing

Fig.8 shows a routing and channel allocation result obtained by the proposed algorithm for the example network in Fig. 2. It first calculates the possible minimum number of hops from each active node to the sink node. For each egress edge e of node n, with distance D, it calculates $U(e)$, $R(e)$, $P_{TX}(e)$, $P_{eff}(e)$ and then Cost metric from them.

The algorithm allocates, whenever possible, a new channel to each selected edge so the edges can have a maximal utilization ratio. If all the channels have been used, however, it reallocates a channel in a way that minimizes the channel utilization ratio $UR_c(e_i)$.In this example, we assume that 5 channels are available, and as a result, no channels are shared.

For edge e_2 from node $n2$, D=2 (indicating 20 m), $U(e)$=20 Mbps, $R(e)$=90 Mbps, $P_{TX}(e)$ = 276 mW, $P_{eff}(e)$ = $P_{TX}(e) \times UR(e)$ = 276 x 20/90 = 61.3 mW (indicated by EP). Here edge e_2 is selected and added to E, since it is the only path from $n2$ to $n0$ (sink).

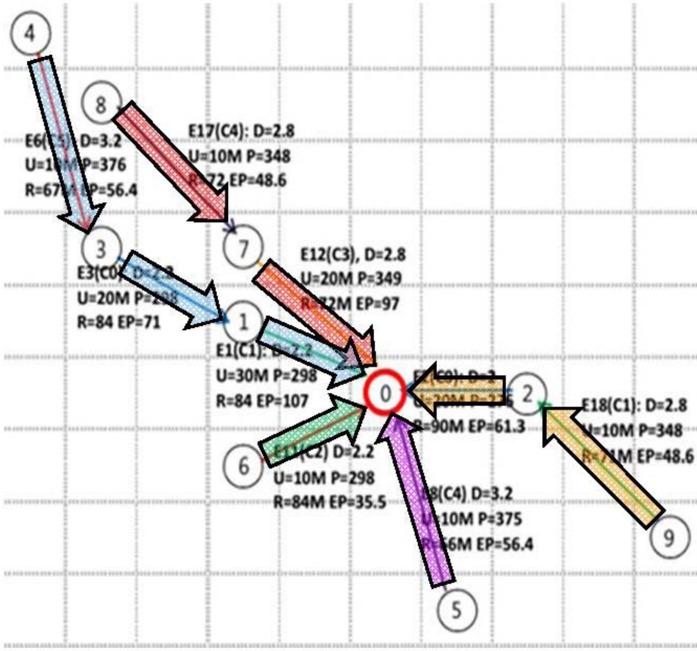

FIGURE 8
Example routing and channel allocation result from the proposed algorithm, when applied to the wireless video sensor network of Fig. 2.

In the same way, for edge e_8 from node $n5$, $P_{eff}(e)$=56.4mW. For edge e_{18} from $n9$, $P_{eff}(e)$=48.6mW, while for edge e_{19} from $n9$ to $n5$ (not shown in Fig.4), $P_{eff}(e)$= 56.4mW. Therefore, cost metric $CM^{path}_{n9,s}$ =61.3 + 48.6 = 109.9 for the path n9 → n2 → n0, while $CM^{path}_{n9,s}$ =56.4 + 56.4 = 112.8 for the path n9 → n5 → n0. The algorithm selects the former path since it has a lower cost metric.

In this fashion, the algorithm selects the best edges of E as shown in Fig 8. At the same time, it allocates minimal number of channels to the edges, so the edges in vicinity $V(e)$ would not interfere with each other. In Fig.8, different channels are indicated by different colors and also by channel IDs, C0~C10.

The final routing paths in Fig.8 are:

<n2→n0>, <n5→0>, <n6→0>, <n1→0>, <n7→0>, <n9→0>, <n3→1→0>, <n8→7→0>, <n4→3→1→0>

Fig.9 shows a result of another routing algorithm with a different cost metric,which selects paths that maximizes each route's data throughput. The path for n4 is selected as:

<n4→3→7→0>

Fig.10 shows a result of the next routing algorithm with a cost metric, which finds each link that has maximal link rate. Its routing results are:

<n2→0>, <n5→2→0>, <n6→0>, <n1→0>, <n7→1→0>, <n9→5→2→0>, <n3→6→0>, <n8→3→6→0>, <n4→8→3→6→0>

It can be observed that Fig 9 and Fig 10 result in route paths with higher power consumption than Fig 8.The total TX power consumption is 1.66W for Fig. 8 (the proposed algorithm), 1.70W for Fig. 9, and 2.38W for Fig 10. (See the 2^{nd} column of Table2).

D. Routing Algorithm with Channel Sharing

Incremental UR_C Calculation:

While selecting each edge *e* as a route, the algorithm allocates a channel that is disjoint from its neighbor edges if possible. If no disjoint channel is left, it reuses a channel in a way that minimizes $UR_C(e)$.

Each time an edge *e* is selected as a route, the heuristic algorithm incrementally updates $UR_C(e)$ by the following formula:

$$For\ each\ e_a,\ \forall n_v \in W_a$$

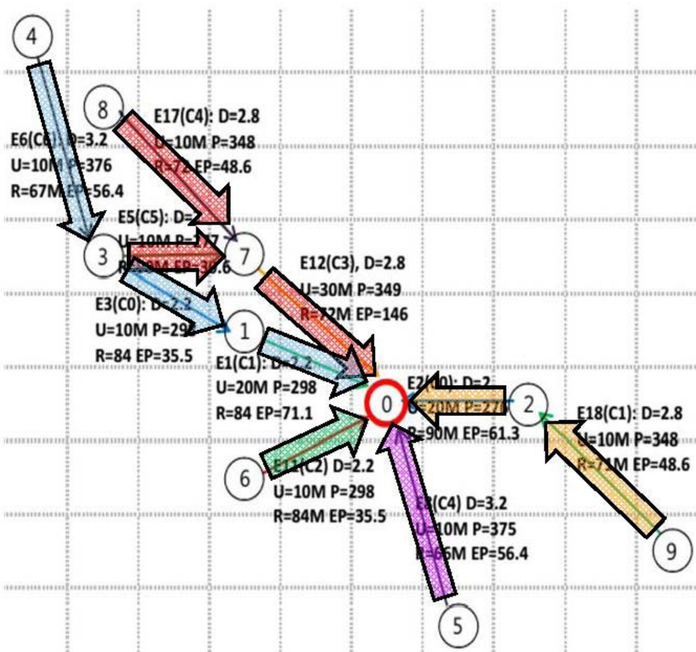

FIGURE 9
A result using a routing algorithm that selects paths maximizing each route's data throughput. (Applied to the network in Fig 2).

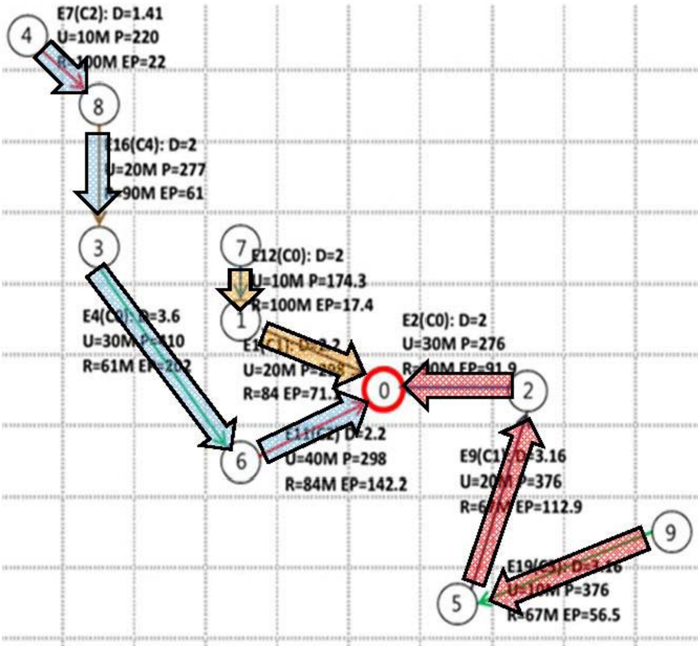

FIGURE 10
A result using a routing algorithm that selects links that have maximal link rate. (Applied to the network in Fig 2)

$$For\ \forall e_v^{ing} \in V_a$$

$$UR_C\left(e_v^{ing}\right)[c_e] = UR_C\left(e_v^{ing}\right)[c_e] + \Delta UR(e_a)$$

$$c_e \text{ is a channel ID allocated to } e_a \qquad (14)$$

$$For\ each\ e_i,\ For\ \forall c_i\ of\ e_i,$$

$$\text{Satisfy } UR_C\left(e_i\right)[c_i] \leq 1 \qquad (15)$$

When the routing algorithm selects an edge as a route, as in EQ (14), it considers the edge as an aggressor e_a and finds potential victim edges e_v^{ing} in its wireless rangeW_a. Here W_a is defined as the wireless range from the source node of the aggressor edge e. An ingress edge e_v^{ing} is an edge headed towards a victim node n_v within W_a. EQ (14) then increases e_v^{ing}'s channel utilization $UR_C\left(e_v^{ing}\right)[c_e]$ by the utilization increment $\Delta UR(e_a)$. Here $UR_C\left(e_v^{ing}\right)[c_e]$ is defined as an array of $UR_C\left(e_v^{ing}\right)$ whose entry is indexed by channel ID c_e.

EQ (14) adds $\Delta UR(e_a)$ to the array entry indexed by e_a's channel ID. Here the algorithm uses an increment $\Delta UR(e_a)$ since the total amount $UR(e_a)$ is unknown until the algorithm completes. Whenever the algorithm allocates additional routed data to e_a later, EQ(14) will add $\Delta UR(e_a)$ corresponding to the additional data.

The algorithm finds potential victim edges e_v^{ing} by selecting all the ingress edges headed towards every victim node n_v in W_a. V_a is a set of all victim edges in W_a. Every edge maintains an array of $UR_C\left(e_v^{ing}\right)[c_e], 1 \le c_e \le c_{\max}$ until the algorithm finishes, where C_{max} is the max number of channels available. The algorithm later compares $UR_C(e_i)[c_i]$ when selecting e_i's channel in a way that the lowest channel utilization for e_i can be achieved.

Channel Allocation for Lowest UR_C:

Once $UR_C(e_i)[c_e]$ of candidate edges have been calculated by EQ(14), the routing and channel allocation algorithm selects a route edge e_i as follows. It selects e_i in a way that e_i minimizes $CM_{n,s}^{path}$ of EQ (13), and there is at least one channel c_e whose $UR_C(e_i)[c_e]$ can still carry new data. This way, the proposed algorithm ensures that newly selected edges keep the channel utilization of all neighboring edges as low as possible. It also guarantees that the channel utilization of the previously selected edges would not overflow.Algorithm2 below gives the main procedure of the proposed routing and channel allocation algorithm with channel sharing.

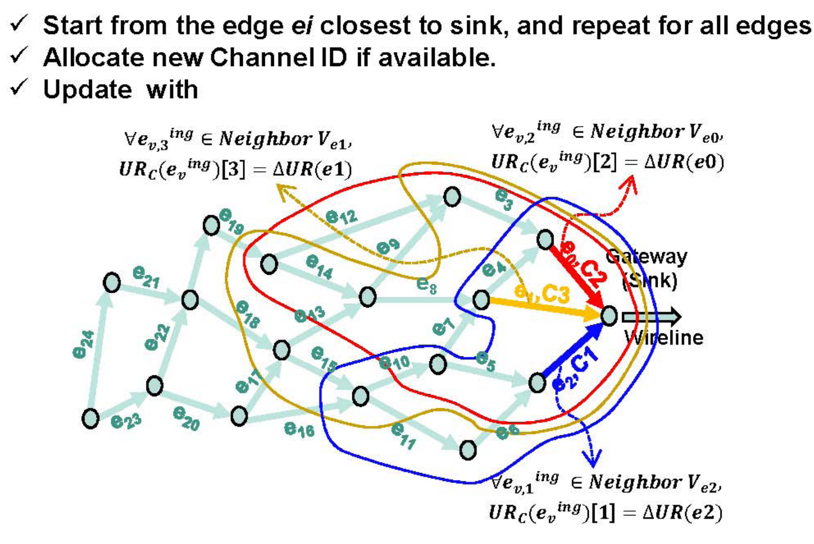

FIGURE 11
Channel allocation Example for the network of Fig 4. Step1: allocating 3 new channels (C1, C2, C3) to the first 3 edges starting from the sink node.

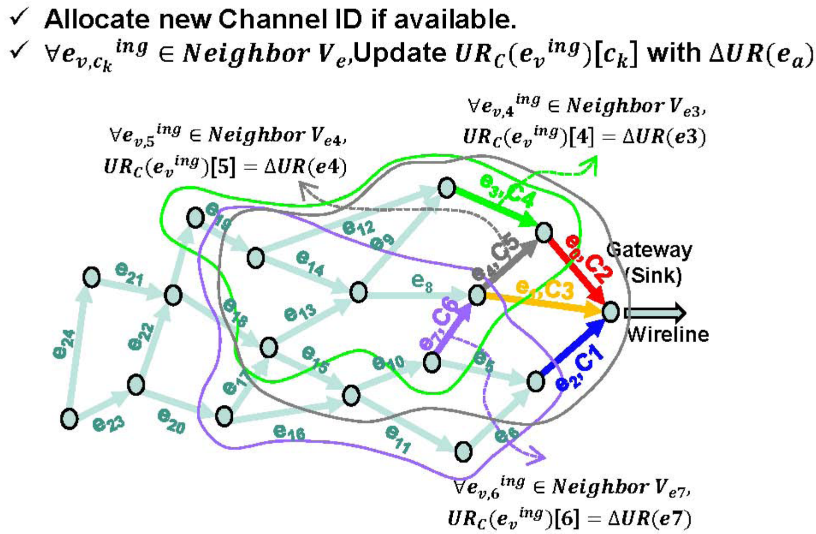

FIGURE 12
Step2: allocating 3 new channels (C4, C5, C6) to the next 3 edges following step 1 in Fig 11.

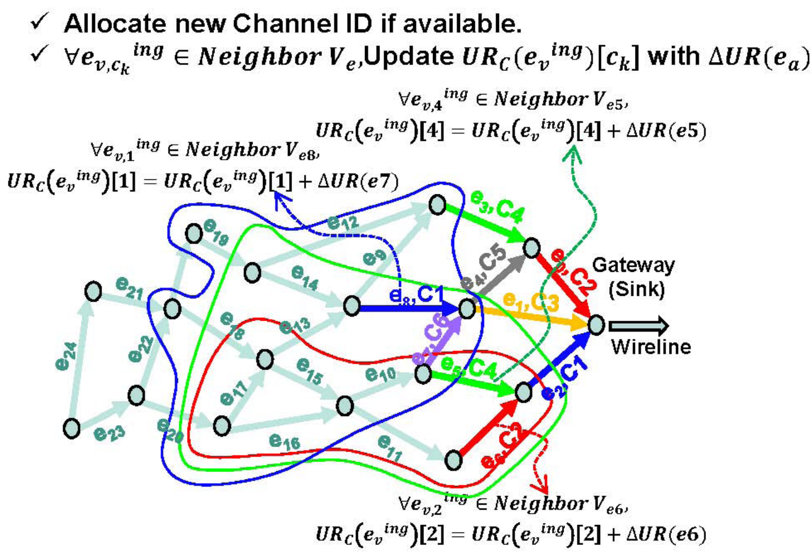

FIGURE 13
Step3: allocating old channels (C1, C2, C4) to the next 3 edges following step 2 in Fig 12.

E. Routing Example with Channel Sharing

Figs.11–13 illustrates example channel allocation steps. In Fig.11, the proposed routing algorithm selects e_2, then the channel allocation algorithm selects channel 1 for e_2. It then finds a victim set V_{e_2} of neighbor edges, which are ingress edges e_v^{ing} to all the nodes within W_a from the source node of e_2.

Algorithm2: Routing and Channel Allocation With Channel Sharing

Input: *V = the set of all active nodes, s = sink node, w_i = the wireless range of active node v_i,*
u_i = the bit rate of video sensor of node v_i, c_{max} = the max. number of channels available
Output: *P_{eff}^{net} = Sum of TX power, RouteSet = the set of selected paths, ChannelSet = the set of seleted channels*

Let V_L be a list of $v \in V$ ordered with distance. Let E be the set of all edges. Initialize E = empty.
For $v \in V${ / Sort the nodes in the order of distance */*
Let $d(v,s)$ be the distance from v to Sink node s.
Add v with the next minimum $d(v,s)$ to V_L.
}
For the next v_i in V_L{ / Calculate utilization ratio of the ordered list of nodes */*
$\{CM_{vi,s}^{path}, path_{i,s}\}$ = ***search_for_route_channel***(v_i)
/ If $CM_{vi,s}^{path} = \infty$, v_i is unroutable, else v_i has a routing $path_{j,s}$ with an effective TX power $CM(e_{i,j})$ */*
if $CM_{vi,s}^{path} \neq \infty$, then $P_{eff}^{net} = P_{eff}^{net} + CM_{vi,s}^{path}$, RouteSet = Insert ($path_{i,s}$), ChannelSet = Insert ($c_{i,j}$)
}
***search_for_route_channel* (v_i)**{
/* This function is the same as Algorithm 1 */
}
***select_channel* e_a** {
Let n_a be the aggressor node and also the source of e_a
Let n_v be a victim node within the wireless range w_a of the aggressor n_a
SEL_NEXT_CH:
For each c_k that are not marked as over-loaded /* $0 \le c_k < c_{max}$ */
For every $n_v \in W_a$
For everye_v^{ing}/ Let e_v^{ing} be an ingress edge of n_v*/*
$UR_{c,max}(e_v^{ing})$ = MAX($UR_c(e_v^{ing})[c_k]$} /* e_v^{ing} is an ingress */
$c_e = c_k$ whose $UR_{c,max}(e_v^{ing})$ is the minimum /* c_e is a channel ID allocated to e_a */
For every $n_v \in Wa${
For every e_v^{ing}{ / Let e_v^{ing} be an ingress edge of n_v */*
$UR_C\left(e_v^{ing}\right)\left[c_e\right] = UR_C\left(e_v^{ing}\right)\left[c_e\right] + \Delta UR(e_a)$ /* Increase the UR_c for channel sharing */
if $UR_c e_v^{ing}$ $[c_e]> 1$, then mark c_e as over-loaded and go to **SEL_NEXT_CH**
}
}
if all c_k's are marked as over-load, then Return (NULL)
else Return (c_e)
}

For all e_v^{ing}, it then updates $UR_C(e_v^{ing})[1]$ with $\Delta UR(e_2)$. Similarly other edges e_0 and e_1 are allocated with channels 2 and 3, and then $UR_C(e_v^{ing})[2]$ and $UR_C(e_v^{ing})[3]$ are updated for V_{e_0} and V_{e_1}, respectively.

Fig. 12 shows step 2 of the channel allocation. The routing algorithm selects the next route edges, e_3, e_4, and e_7. The channel allocation algorithm selects new channels, 4, 5, and 6 for these edges. As in Fig.11 (step 1), $UR_C(e_v^{ing})[c_e]$ is updated for all potential victim edges with $c_e = 4$, 5, and 6, respectively.

Fig. 13 shows step 3 of the channel allocation example. For selected edge e_6, no new channel is available. The algorithm, therefore, selects c_e from old channels in a way that makes $UR_C(e_v^{ing})[c_e]$ minimum. In this example, channel 2 is selected. Then it increases $UR_C(e_v^{ing})[c_e]$ of all victim edges by $\Delta UR(e_6)$. Similarly it selects old channels 4 and 1 for selected route edges e_5 and e_8.

Fast and Highly Accurate Algorithm:
To avoid an exhaustive search, the proposed algorithm, in each step, selects the best route edge and channel using partial $UR_C(e_v^{ing})[c_e]$ which has accumulated utilization increment $\Delta UR(e_a)$ only for the route edges selected until the current step. For the best edge selected, the algorithm recursively searches the next best edge towards the sink node. During this recursive search, for all selected edges, partial $UR_C(e_v^{ing})[c_e]$ of all its victim edges is increased by $\Delta UR(e_a)$. If any of $UR_C(e_v^{ing})[c_e]$ exceeds 1, the recursive search backs out, and selects the next best edge and channel. The proposed algorithm, therefore, ensures that $UR_C(e_v^{ing})[c_e]$ of all the pre-selected edges would not overflow by the newly selected edge; an important property of our cost-metric based search algorithm.

This property allows very fast routing and channel allocation, while calculating the partial channel utilization accurately for all the victim edges.

Handling Over-Loaded Video Data:
In this paper, we attempt to find a routing and channel allocation solution such that each selected link satisfies EQ (15), which is $UR_C(e_i)[c_i] \leq 1$. Such solution ensures that the video data from each active nodeis transferred to sink at the speed of real time. If there is any link that cannot satisfy EQ (15), such link would have over-loaded video data, and its video buffer may be backed up. As for such links, the power model of EQ (10) still estimates accurately power consumption but with the condition $UR_C(e_i)$ $[c_i]>1$. We can easily extend the proposed algorithm to cover such cases. We assume in this paper that the video stream data is generated only during a short period of active time, and the video buffer would not overflow. For the sake of emphasizing the efficiency of the proposed method, we consider only WVSNs that have solutions satisfying EQ (15) in the remainder of the paper.

IV EXPERIMENTAL RESULTS

We implemented a network simulator (WiSeR) based on the the proposed algorithm. We experimented with an extensive set of wireless video sensor networks. We first experimented WiSeR with an unlimited number of available channels to evaluate the power consumption of the proposed routing algorithm based on utilization ratios. Experiments with limted channels are shown later.

Table 1 shows simulation results of 10 networks whose size ranges from 100 nodes to 400 nodes. The number of active nodes ranges from 9 nodes to 100 nodes. (See Table 1). The positions of active nodes are randomly selectedfor each network to generate various network structures. For each of the networks, the proposed routing and channel allocation algorithm creates a near optimial multi-channel mesh network. The resulting mesh network connects all the active nodes in a way that ensures the transfer of all video data at real time speed (by EQ(12)) using as low power as possible (by EQ(10)).

We implemented three different routing algorithms and applied them to a set of 10 WVSN networks described above:

***Routing for High Rate Link*:** Selecting each edge with the highest link rate.

***Routing for High Route Throughput*:** Selecting edges so the overall route has max throughput.

***Routing based on Min Utilization*:** Proposed method for low power.

Table1 compares the results of the 3 algorithms. It shows the number of routable paths. For some network of large size, some paths turned out as unroutable owing to its high congestion. WiSeR produced all paths routable except the 2 largest network cases, which is better than the other 2 algorithms.

Fig. 14 compare the total TX power consumption of the 3 algorithms described above. WiSeR has the lowest TX power in all cases. WiSeR achieved up to 70% lower power than the algorithm for high rate link, and up to 30% lower power than the algorithm for high throughput.

Number of Routable Paths

Num. of Active Nodes	9	20	30	40	50	60	70	80	90	100
Routing for High Rate Link	9	20	24	40	50	60	70	80	90	94
Routing for Route throughput	9	20	30	40	50	57	67	74	82	86
Proposed Routing for Low Power	9	20	30	39	50	58	68	76	82	89

TABLE 1
Simulation result of WiSeR: Comparison of the number of routable paths for 3 different routing algorithms.

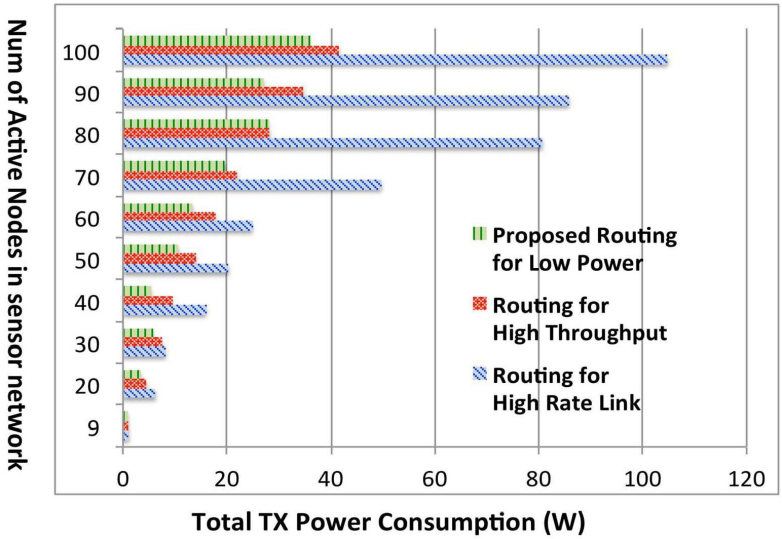

FIGURE 14
Comparison of total TX Power consumption for the 3 different routing methods.

Next we present more experimental results of WiSeR with limits on the number of channels. We used 3 channel allocation methods with the following cost metric:

Round-Robin: Select one channel in round-robin fashion among all channels whose $UR_c(e_v^{ing})[c_e]$ do not overflow for all pre-selected edges.

Minimum Utilization: Select a channel of the lowest $UR_c(e_v^{ing})[c_e]$ among all channels whose $UR_c(e_v^{ing})[c_e]$ do not overflow for all pre-selected edges.

Min. Neighbor Utilization:Proposed method of channel allocation. First find, for each c_e, $UR_{c,max}(e_v^{ing}) = \mathrm{MAX}(UR_{c,max}(e_v^{ing})[c_e]$, for $\forall e_v^{ing} \in V_a)$. Then select channel c_e that corresponds to the minimum value of $UR_{c,max}(e_v^{ing})$.

Fig.15 gives routing results of WiSeR under the given channel limits: the number of routable paths for the above 3 channel allocation methods. The Min. Neighbor Utilization method finds all routes for all active nodes. For the other 2 methods, on the other hand, some paths turned out as unroutable owing to the excessive congestion level under the limited channel count.

Fig. 16 shows the number of channels required to complete the routing and channel allocation for the 10 example networks. The Min. Neighbor Utilization method gives the best results for all cases. The other 2 methods, however, could not finish the channel allocation for some networks.

Fig. 17 compares the total TX power consumption of the 3 channel allocation methods. The min. neighbor utilization method has the lowest TX power in most of the networks. It has up to 30% lower power than the

Table 2: Routing results of WiSeR under given channel limits

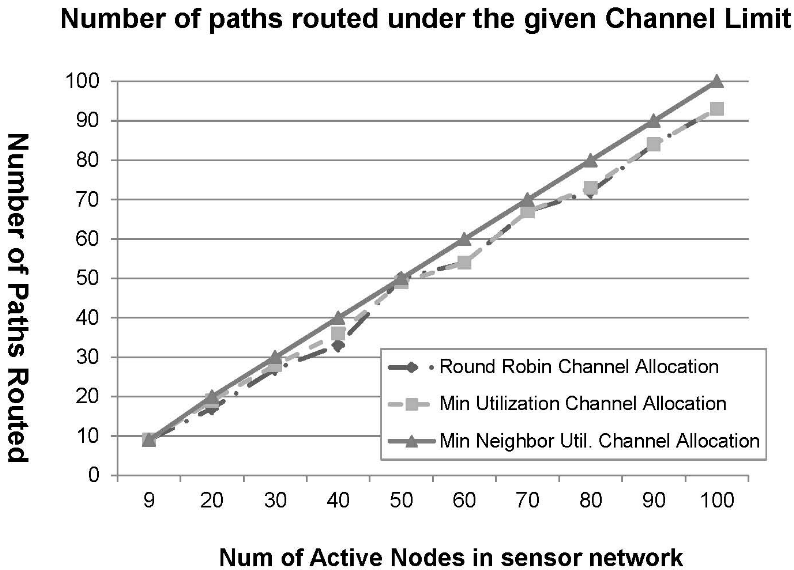

FIGURE 15
Comparison of total TX Power consumption for the 3 different routing methods.

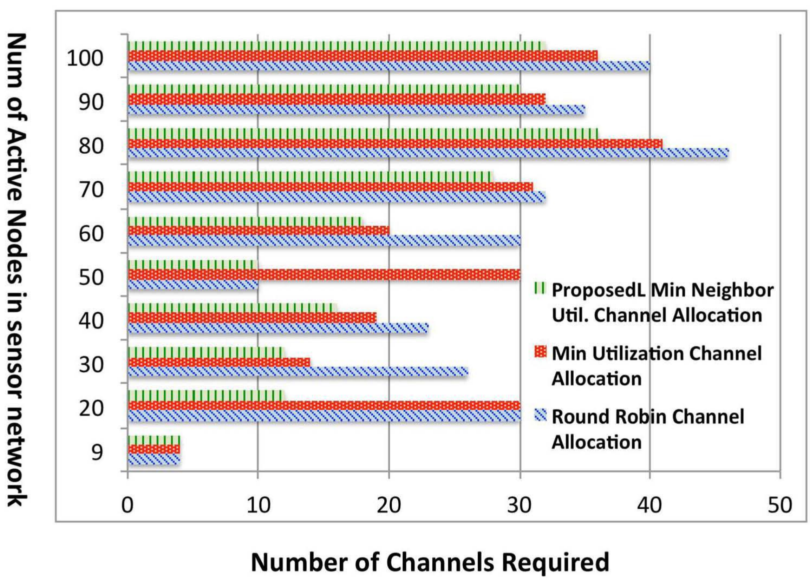

FIGURE 16
Comparison of the number of channels required to finish routing and allocation

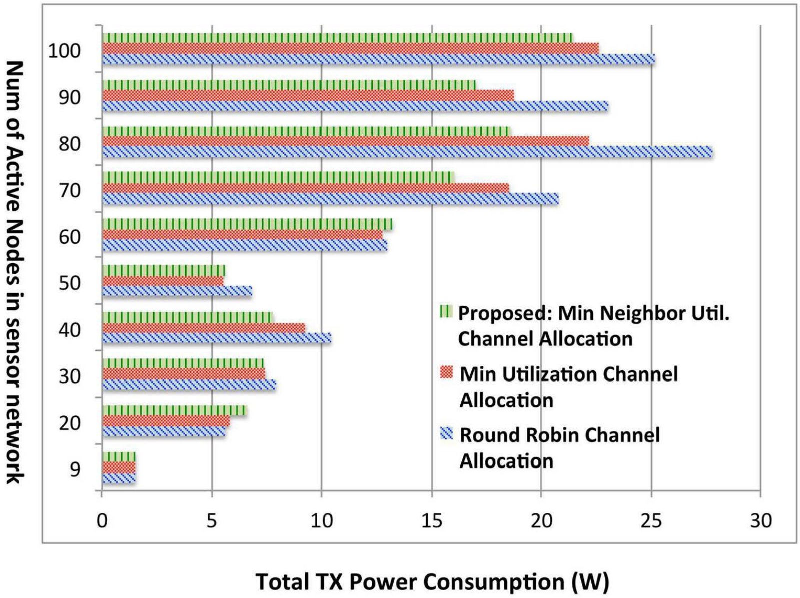

FIGURE 17
Comparison of total TX Power consumption for the 3 different channel selection methods.

round-robin method, and up to 15% lower power than the min. utilization method.

In this paper, we assume that the routing and channel allocation are processed in a central node. We hence assume that a central node collects other node's information periodically (e.g. wake-up or sleep mode, data rate, and event-detection information), and then broadcasts routing results.

The proposed algorithm can also be implemented as a distributed routing method. In a distributed method, a node that detects an event broadcasts its information to its vicinity nodes; then the node and its vicinity nodes can recalculate their routing and channel allocation.

V CONCLUSIONS

Wireless networks of battery-powered cameras with an event-driven wake-up function are becoming an increasingly important application area for Internet of Things (IoT). We presented our recent work on multi-channel multi-hop routing algorithms for wireless video sensor networks. We presented a modeling technique for wireless sensor networks with realistic transmission (TX) power based on the link utilization and shared-channel utilization. We then proposed formulation for optimal routing and channel allocation for minimal power. A heuristic utilization-aware algorithm (WiSeR) has been implemented. Extensive experiments have been conducted with 3 different routing algorithms and 3 different channel allocation cost metrics. The results have shown that the proposed utilization-based routing algorithm reduced up to 70% of TX power, while the proposed channel allocation method saved up to 30% of TX power compared with other methods. The proposed work is expected to contribute to the new research areas of Internet of Things such as wireless video sensor networks.

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