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ABSTRACT

Community Wireless Networks (CWNs) have recently emerged as a top priority for many communities world-wide to access the information highway and bridge the digital divide. There are many factors that contribute to the development and the sustainability of a successful CWN. These factors include traditional technical network parameters in addition to several social and economic parameters. This paper proposes a two-graph model for describing CWNs. The proposed graph model uses well established graph concepts to depict the key factors needed to be addressed when analyzing and designing CWN. We show how the two graphs; the social network graph and the wireless network graph are used to model CWN factors. We also show how the proposed model was used in a case study to support the Omaha Wireless project. We argue that having such a quantitative model represents a significant step towards better understanding of CWN and advancing this timely research area.

Keywords

Community wireless networks, socio-technical networks, graph theoretic models, economic benefits of wireless networks.

INTRODUCTION

Providing a simplified and quantitative description for CWNs is essential for scientists to address related issues and for practitioners to bear fruit from them. When two roommates, family members, or neighbors lease an Internet line and share an access point with each other, they have just created a simple CWN. A more complex form of CWNs is created when a big community (or municipality) shares a few access points developing a mesh of wireless network. Such networks could grow, or concatenate with other wireless clouds and WiFi hotspots, to form a city-wide wireless network (Sandvig, Young, and Meinrath 2004). CWNs have been established in many cities all over the world including New York, Austin, Seattle, San Francisco, USA; Paris, France; Hamburg, Germany; and Turku, Finland (Abdelaal and Ali 2007; Quinn 2006; Vos 2005). These networks are created and maintained by the contributions of local communities and advocates. Community contributions may include sharing their access points with their neighbors and other community members; donating money and old computer hardware to build the network; developing software for the system, or providing manpower and technical support (Abdelaal and Ali 2007; Quinn 2006; and Wilco 2004). Therefore, the shared resources of communities (e.g., times, effort, money donations, skills, beliefs and values and computing resources) are the main resources for building and maintaining these networks.

Recently, community and municipal wireless networks have gained momentum and attracted many practitioners, nonprofit organizations, technology vendors and communities. However, there is a lack of scientific studies and general models that describe and analyze these emerging networks. In addition, the majority of previous work is made by practitioners and the quality of their research findings depends on their experience or values. In this paper, we apply graph theoretic approach to provide a simple and a compact model (or artifact) that describes such complex systems. This research is situated in the design-science paradigm that seeks to extend the boundaries of human knowledge by creating new Information Technology artifacts. These artifacts include constructs, models (or abstractions), methods (algorithms and practices), and prototypes (Hevner, March, Park, and Ram 2004).

A graph is a mathematical model consisting of two sets V and E. V is a set of nodes called vertices connected by a set of links (or E) called edges, and it has been used to describe many complex systems (Gross and Yellen 2005). For instance, the Internet is best described as a graph of routers and computers linked by physical or wireless links. Social structures are described as graphs of individuals (or organizations) linked by social relationships. Peter, Scott, and Wasserman (2004, pp93) summarized several benefits for using graph theory to represent complex networks:

- Graph theory provides the vocabularies, concepts and the mathematical operations that could be used to label, denote, quantify and measure the system variables in a single model;
- Graph theory gives us the ability to prove theories and deduce testable statements related to complex networks. For instance, if the matrix of the graph is symmetric, that means the benefits and the contributions of the CWNs' actors are equal;
- Using such quantitative artifacts to represent the interactions between actors makes it easy for researchers to understand and measure causality between variables.

In this work, we develop a simplified quantitative description of CWNs helps to understand the confluence and the interactions between their social and technical variables, and this is a necessary starting point for studying such complex systems. We view each CWN as two graphs: a social network (or graph) and a wireless network (or graph). The properties of these two graphs and the interactions between them provide insights about the overall system and its functionality.

RELATED WORK

Quinn (2006) proposed a guide on how to build CWNs based on multiple case studies. This guide points out the role of community engagement, volunteerism, OSS, and donated computer and wireless technology in the creation of CWNs. The community of Leiden, Netherlands, built a low-cost wireless network using low cost network technologies, OSS, home-built antennas, and voluntary manpower and technical support (Drunen, Koolhaas, Schuurmans, and Vijn 2003).Wilco (2004) believes that the success of CWNs depends on contributors benefiting from these projects. He points out that sprit of such projects is recognizing that every community member has the potential to contribute something. Huysman and Wulf (2004) argue that electronic networks encourage the formation of social capital. Kavanaugh and Patterson (2001) state that community computer networks have positive impact on social capital because they bridge the digital divide and increase access to information.

Wilco (2004) identified the key business partners in the Austin Wireless project include Dell Recycling Program and Image Microsystems to recycle old equipment. According to Wilco, Austin wireless also collaborates with OSS communities such as Linux, Apache, NoCatAuth, and Postnuke. Moreover, local schools provide student interns to help with network installation in exchange for experience. Also, job seekers volunteer to obtain expertise. In addition, public libraries host the facilities to obtain free WiFi access. It is important to assess the contributions and the benefits of these actors in order to empower them and replicate the project in similar communities. Abdelaal and Ali (20007) employed the business model concept to address the stakeholders, value proposition, target customers, and resource management for different types of community and municipal wireless network. The authors classified the business models of municipal and community wireless networks into six categories: public utility; ad-supported, education-centric, community, public-private, and location-hosting. The authors provided examples of these business models, elaborated on their components, and identified their advantages and disadvantages. For a wide range of CWNs' cases with more details about their implementation models and the role of community members in boosting this innovation, we refer readers to Abdelaal and Ali 2007; Mandviwalla, Jain, Fesenmaier, Smith, Weinberg, and Meyers 2006; Quinn 2006; and Vos 2005).

Abdelaal and Ali (2008) proposed a multiple-tier pricing policy for community and municipal wireless services that considers the social and economic objectives of these projects. This policy provides the service access for free and charges users based on the consumed bandwidth of their applications weighted by the average packet delay. The findings of their experiments show that users who run data applications (e.g., web browsing and email) could have the service for free due to the minimal bandwidth consumption of data applications. While authors suggested charging users who run audio and video applications only, they advise network operators to set a higher price rate for video applications due to their high bandwidth consumption.

The concepts of graph theory have been used to model similar complex systems and solve related problems in different domains such as computer networking, social networks, biology, chemistry, physics, and transportation. For instance, they have been used to analyze peer-to-peer systems (Loguinov, Kumar, Rai, and Ganesh 2005). The findings of this study show that the de Bruijn graphs is most appropriate for designing peer-to-peer systems since it has short average routing distances, big diameter, and high connectivity and high resilience to node failure compared to other examined structures. Jackson (2003) discussed many examples of economic applications of graph theory. These applications include obtaining information about jobs from social contacts, exchanging goods with market actors; and contracting trade agreements. Gale and Kariv (2007) propose a graph model for financial networks where nodes represent traders/actors and weighted edges represent the probabilities of trade between two actors. Souma, Fujiwara, and Aoyama (2005) modeled the Japanese shareholders network using a directed graph where nodes represent companies and edges represent activities, ownership, and governance. Spulber and Yoo (2005) used graph concepts to price telecommunication services. Their proposed pricing policy takes into account the impact of changes in one node on the entire system, particularly on the economies of scale.

A GRAPH THEORETIC MODEL FOR CWNs

The realm of CWNs lies at the confluence of wireless technologies, nonprofit organizations, and social networks (Abdelaal and Ali 2007). In other words, these networks are socio-technical networks where community members volunteer and donate to build customized wireless networks to fulfill their needs and fit their circumstances. The concept of socio-technical networks represents the interactions between technologies and people where technologies are developed within a social world and supported by technicians and other skillful individuals (Kling, McKim, and King 2001). Therefore, we model each CWN as a socio-technical network using two graphs that we refer to as the social graph and the wireless network graph. The social graph is used to depict the social and economic factors of the community served by this wireless network. These social factors include technology acceptance, community contributions, ownership, and management. The economic factors are service pricing, funding, value proposition, and the incentives provided to volunteers and contributors to empower. CWNs are usually created and maintained through the embedded resources in the community such as voluntary work, donations, partnerships, and using OSS as discussed earlier. These networks boost economic and social development through providing a broad range of benefits to their stakeholders (Abdelaal and Ali 2007; Lehr, Sirbu and Gillett 2004; Mandviwalla *et. al.* 2006; Shamp, 2004; and Quinn 2006). The key benefits they generate during the implementation stage are building physical capital, human capital, and social capital. After the operation of the project, these networks support a wide range of educational, commercial, societal, and medical, and personal application (Abdelaal and Ali 2007; Sege 2005; and Shamp 2004). This is in addition to the inherited benefits of wireless communications in terms of mobility, affordability, time, money, and effort savings, and resource sharing as shown in Figure 1. The wireless network graph is used to model the technical factors of the deployed network such as access point positioning, quality of service (QoS), reliability, signal interference, security, wireless and wireline Integration, data rate, etc (Cisco 2007; Intel 2005; and Lehr, Sirbu and Gillett 2004). Figure 1 represents the social and technical variables of CWNs as complex systems. Identifying these variables has been made based on extensive review of literature, experience of working on one of CWNs projects (the Omaha Wireless), and attending panel discussions during the International Summit for CWNs[1]. This proposed model, however, might be changed or modified based on the findings of future work. Standard graph theoretic parameters are used to represent the confluence and the interactions between these two graphs.

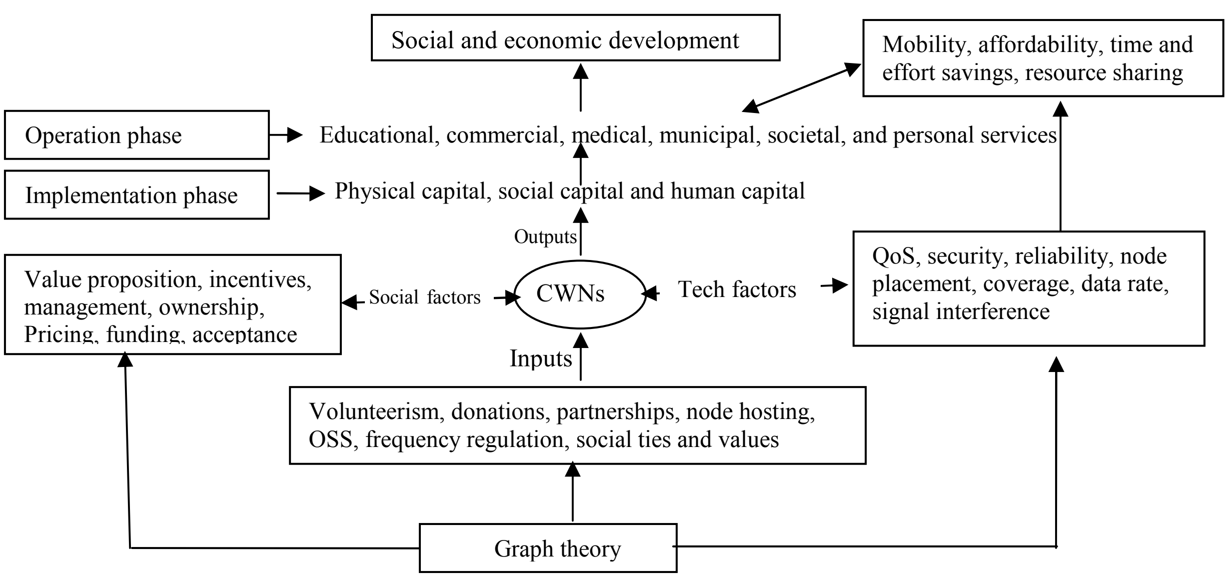

Figure 1. A Graph Theoretic Model for CWNs

Wireless networks are modeled as directed graphs $G_w = (V_w, E_w)$ whose nodes V_w are wireless devices and their links E_w are the wireless signals. These links have attributes such as signal range; signal strength; signal interference; data rate; and signal quality. The directions on the network links are used to identify the directions of the wireless signals.

[1]- The International Summit for Community Wireless Networks, held in Columbia, MD, U.S., from May 18th to the 20th, 2007. The objective of this summit was to explore the opportunities and challenges facing the growing movement of CWNs.

We assume that each wireless network serves a social network represented by a directed graph Gs (Vs, Es), where the set Vs which represents the set of CWNs' actors or stakeholders where Vs = {v1, v2,…, vn}; and the set of social ties Es; where Es = {e1, e2, …, em.}. These ties could be kinship, roommate, neighborhood, friendship, reciprocation, trust, etc. We define each tie eij ⊂ E (Gs), for a pair of actors i and j ⊂ Vs where eij =1 if there is a tie between i and j, and 0 otherwise. These ties could be weighted by the distance between these actors, the flows of tangential or intangible values between actors, or the strength of these teas. For the set Vs, we have three categories of actors: beneficiaries, contributors, and isolated nodes. Beneficiaries are the individuals who benefit from CWNs. These benefits could include obtaining free Internet access, donated PCs, technical expertise, or spiritual benefits. Contributors are those who contribute to build and maintain the system. Contributions may include providing voluntary work or technical skills, donating money or old equipment, hosting a wireless node, or boosting the publicity of the project. Table 1 provides examples of these beneficiaries and contributors. For more examples about possible contributions and benefits, we refer readers to (Abdelaal and Ali 2008; Mandviwalla et al. 2006; and Quinn 2006) Isolated nodes are those individuals who are not part of the network. In other words, they are the individuals who neither benefit from the network nor contribute to it and a typical example of these individuals is those who do not have Internet access and the people who have wireless access points and do not share them with anyone. Two different actors, i and j, of a graph are said to be adjacent (or neighbors) if there is a social tie between them and both of them live in the range of the wireless signal. To illustrate, contributors of the NYCwireless project share their access point with their neighbors for different reasons. This is why these networks are called *"neighborhood wireless networks"* sometimes.

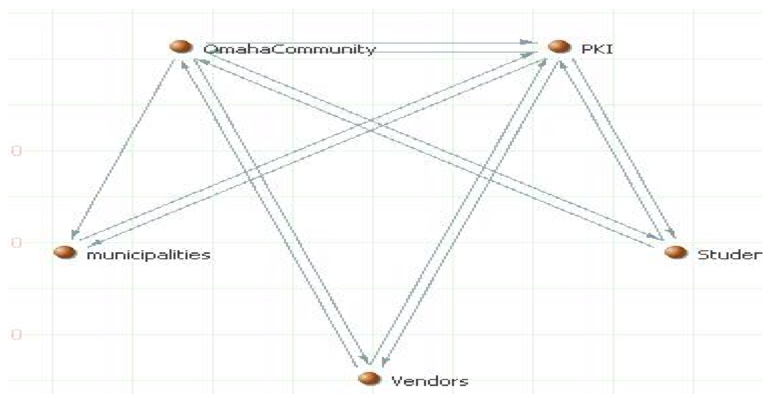

Figure 2: The Main Actors of the Omaha Wireless Network

This set of actors Vs represents a specific social clique such as family members, roommates, neighbors, friendship circles, library visitors, church attendees, business partners, co-workers, university students or any social network that are related one way or another and share a specific wireless network. It is important to note here that a social network in a geographical locality or neighborhood could be clustered to various cliques or sub-groups based on specific parameters as shown in Figure 2. It shows that the stakholders of the Omaha Wireless project could be clustered based on their common attributes into five groups: the PKI administrators, Students, the Omaha community, technology vendors, and municipalities. We assume that each wireless network serves a cluster of these social networks or a mix of them. In addition, this set of actors could include other stakeholders and beneficiaries such as underserved and remote communities, the mobile workforce, healthcare providers, telecommunication companies, municipalities, OSS developers, civic activists, and technology vendors (Abdelaal and Ali 200; Mandviwalla et. al. 2006). These actors have qualities (e.g., attributes, behaviors, values, attitudes, and motivations). They either contribute to build the system or benefit from it. Edges may have weights to represent the quantitative values of the benefits and contributions of these actors.

For the purpose of this study, if all members of the social network are electronically disconnected, we have an empty wireless graph. If the community is socially connected and electronically disconnected we call it "a quasi-connected community." We believe that there is always a technical solution to wirelessly connect such a community, taking advantage of the unlicensed 2.4 GHz spectrum and the embedded resources in the community. The community is described as "fully connected" if and only if it is socially connected and electronically connected. If the access point serves its owner only, it creates a trivial wireless graph with only one node. A trivial CWN is a network on one person in which the person is connected to the Internet, has an access point and does not share his/her signal with anyone. This is another example of isolated nodes (or actors). Assuming that every person has potential to contribute (e.g., money, effort, time, skills, etc), how can we convince all members of the community to be part of the project?

These are some definitions and insights that could be deduced by using the graph theoretic approach to model CWNs.

The Omaha Wireless project

The Omaha Wireless project is built and maintained by voluntary students from the Peter Kiewit Institute (PKI) at the University of Nebraska at Omaha's College of Information Science and Technology. This project began as an extension of a research project, aimed at achieving "*digital inclusion*." It provides free WiFi access at the University campus and its neighborhoods, Elmwood Park, Washington Library, and Rosenblatt Stadium. The project managers obtained a donation of two access points from Cisco systems, Inc to support the project. They also negotiated with city officials to obtain the right of way to install the system facilities at public locations. Table1 summarizes the contributions and the benefits of these different actors. The rows represent the contributions of these actors and the columns represent their benefits as obtained from the project plan and discussions with participants. For instance, students contribute their technical skills to Omaha community and improve the reputation of PKI by participating in this project. They obtain experience, exposure, and free Internet. Municipalities give the project managers permission to install the access points in public places such as Elmwood Park, Washington Library, and Rosenblatt Stadium. The benefit that Omaha municipalities obtain is gaining high reputation among constituents.

	PKI	Students	Omaha community	Vendors	Municipalities
PKI	0	Experience , free internet	Free internet, old PCs, civic engagement	Publicity	Reputation
Students	Reputation	-	Technical skills	0	
Omaha community	Publicity	Exposure	-	Publicity	Reputation
Technology vendors	Access points	0	Access points	-	0
Municipalities	Access to public places	0	0	-	-

Table 1. The Contributions and Benefits of Actors of the OmahaWireless Network

One important benefit from the proposed model is helping us to use tools of social network analysis (SNA) to analyze the OmahaWireless related problems. We used the Agna (2007) software to visualize the relationship and the interactions between the main actors of the Omaha Wireless network as shown in Figure 2. Visualizing these systems uncovers hidden information about the properties of these networks and the interactions between their components.

For instance, it can identify the types of actors and the patterns of interactions between them. In addition, visualizing the business partners involved in CWNs and depicting the value flows between these partners can reveal a lot of information about their implementation models and benefits. It can also help to explain how these systems are created and maintained by the community members. In addition, it helps to detect the properties of these networks and the similarities and the differences between their different components. It also shows the connected nodes, disconnected nodes, cut sets, and bridges. It can also help to identify the causes of observed events and analyze risk and fault tolerance of the system when we visualize both the social network and the wireless network and the interactions between them.

Analysis and Design of Community Wireless Networks

As mentioned earlier, the proposed graph theoretic model provides an excellent mathematical tool to address a number of key issues in the design and analysis of CWNs. One of the issues related to CWNs is the need to assess the benefits and the contributions of CWNs stakeholders. This process is important in order to empower participants and replicate the project in similar social settings. CWNs' actors could be classified into contributors, beneficiaries and isolates. The edges between these actors denote their benefits and their contributions. We can represent them in matrices and apply mathematical operations on them as shown in Table 1. Table 1 shows the benefits and contributions of each player in the Omaha Wireless project. However, we should assign money values to these benefits and contributions to deal with them using operations of matrices and graph theories and this is one of our future objectives. For example, if the matrix of the graph is symmetric, that means the benefits and the contributions of the CWNs' actors are equal. The in-degree and out-degree concepts could be used to measure the social and economic impacts of CWNs on the level of individuals, groups, and the society at large. In addition, it could be used to provide in-depth analysis of CWNs stakeholders. For instance, Table 2 shows that PKI and the Omaha community have the highest outdegree which is 0.8. This means that these two actors contribute the most in this project. The indegree of PKI is 0.8 which means that it benefits the most from this project and the Omaha community is the second beneficiary of indegree of 0.6. However, we need to assign money values to these measures in order to assess the social and economic benefits of these actors.

Node	Outdegree	Indegree
PKI	0.8	0.8
Students	0.4	0.4
Vendors	0.4	0.4
municipalities	0.2	0.4
OmahaCommunity	0.8	0.6

Table 2. Distribution of Outdegree and Indegree in the Omaha Wireless Network

Another key fundamental problem facing the design of CWNs is how to identify the best location to install a new node or to place the central management unit. The access points should be installed in places that serve as many users as possible and provide the best signal quality. Graph theory provides a number of concepts that could be used to identify the center of graphs. We used the *graph center* measure to solve this problem. The Concept of graph center is defined as the node whose largest distance to other parts of the graph is minimal. Specifically, the entity with the highest graph centrality measure should host the access point or the central management unit in order to connect as many individuals as possible. Table 3 shows that PKI has the highest centrality of 5.0. Therefore, the PKI should host and manage the system facility because it is located between all other players.

Node	Graph Center
PKI	5.0
Students	0.0
Vendors	0.0
municipalities	0.0
OmahaCommunity	2.0

Table 3. Distribution of Graph Centrality in the Omaha Wireless Network

A third key question facing CWNs is identifying the business model that is most suitable for a specific social setting (Abdelaal and Ali 2007, Cisco 2007). We propose using the Sociometric Status measure to identify the business model that is most suitable for a specific community. Sociometric Status measure is defined as the contribution a given actor provides to the community. The PKI has connections with all other players and it brokers their contributions to build and maintain the system. Since PKI contributes the most and its primary function is delivering education, we can locate the Omaha Wireless network as an education-centric CWN business model. For a review of community and municipal wireless business models, we refer readers to Abdelaal and Ali (2007) and Cisco (2007).

Node	Sociometric Status
PKI	2.0
Students	1.0
Vendors	1.0
municipalities	0.75
OmahaCommunity	1.75

Table 4: Distribution of Sociometric Status in the Omaha Wireless Network

There are other problems that could be solved with the help of this graph model. For instance, given a specific social network $G_s = (V_s, E_s)$, where V_s is the set of nodes and E_s is the set of links between these nodes, what is the minimum number of access points required to cover this community? We argue that the answer for this question depends, in large part, on the social variables of the network such as community size, the network diameter, the social ties between members, and the average data rate per user, and this is one our future research directions. These are some of the insights and hypotheses that we can deduce from this graph representation of CWNs.

IMPLICATIONS FOR PRACTICE AND FUTURE WORK

We have used a graph theoretic model to describe the social and technical variables of CWNs and the interactions between them. In particular, we used the outdegree measure to represent the flows of contributions (tangible or intangible) of a particular actor in creating the network. These contributions may include sharing the wireless signal with others, donating money to build the system, donating IT equipment, hosting the system facilities, and volunteering time and technical skills to build the system and develop necessary software. The most significant aspect of using graph theory in the domain of CWNs is the ability to solve a number of key problems using well defined algorithms such as identifying proper places for positioning access points using the concept of graph centers or finding the best grouping of nodes in the network using the concept of clustering in graphs.

The proposed model, represented in Figure 1, provides a rich set of conceptual insights to guide current and future research related to community and municipal wireless networks. Such a socio-technical treatment of CWNs is necessary to capture the interactions between the social, economic, and technical variables of the network. We also hope that the proposed model would expand the problem solving abilities of CWNs practitioners. The main deficiency facing this model is the difficulty to aggregate the tangible and intangible benefits and contributions of CWNs' actors.

The focus of current work is simulating the impact of the social variables (e.g., community size, density of the network, and types of used applications) on the technical factors such as signal interference, QoS, throughput, and the optimal network size. Future work will focus on collecting quantitative data from the OmahaWireless contributors and users to validate this model. In addition, we will collect data to investigate the impact of CWNs on social and human capital. We will also use clustering techniques to group the actors and stakeholders of CWNs based on their attributes, contributions, and benefits. Another interesting topic that deserves the attention of the scientific community is what incentives should be provided to include isolated nodes and actors in the network?

CONCLUSIONS

We used a graph model to represent CWNs as two graphs: a social graph and a wireless graph. The attributes and the interactions between the components of these two graphs determine different aspects of the network. The proposed model helped us use graph theory measures to solve some related problems. In particular, we proposed using the in-degree measure to measure the benefits that each CWNs stakeholder can obtain. In addition, the out-degree measure could be used to measure the contributions of each actor. The sociometric status measure could be used to choose the business model that best suite a specific community. The graph centrality measure could be used to identify the best location to install a new node or the central management unit. This approach provides a quantitative way to understand and analyze CWNs and tackle related problems. Current work focus on using this model to address design issues of CWNs.

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