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Integrated Cyber-Physical Simulation of Intelligent Water Distribution Networks

Jing Lin, Sahra Sedigh and Ann Miller
Department of Electrical and Computer Engineering, Missouri University of Science and Technology
USA

1. Introduction

In *cyber-physical systems (CPSs)*, embedded computing systems and communication capability are used to streamline and fortify the operation of a physical system. Intelligent critical infrastructure systems are among the most important CPSs and also prime examples of pervasive computing systems, as they exploit computing to provide "anytime, anywhere" transparent services. While the added intelligence offers the promise of increased utilization, its impact must be assessed, as unrestricted cyber control can actually lower the reliability of existing infrastructure systems.

As a practical example, *water distribution networks (WDNs)* are an emerging CPS domain. Physical components, e.g., valves, pipes, and reservoirs, are coupled with the hardware and software that support intelligent water allocation. An example is depicted in Fig. 1. The primary goal of WDNs is to provide a dependable source of potable water to the public. Information such as demand patterns, water quantity (flow and pressure head), and water quality (contaminants and minerals) is critical in achieving this goal, and beneficial in guiding maintenance efforts and identifying vulnerable areas requiring fortification and/or monitoring. Sensors dispersed in the physical infrastructure collect this information, which is fed to algorithms (often distributed) running on the cyber infrastructure. These algorithms provide decision support to hardware controllers that are used to manage the allocation (quantity) and chemical composition (quality) of the water. As WDNs become larger and more complex, their reliability comes into question.

Modeling and simulation can be used to analyze CPS performability, as direct observation of critical infrastructure is often infeasible. Accurate representation of a CPS encompasses three aspects: computing, communication, and the physical infrastructure. Fundamental differences exist between the attributes of cyber and physical components, significantly complicating representation of their behavior with a single comprehensive model or simulation tool. Specialized simulation tools exist for the engineering domains represented in critical infrastructure, including power, water, and transportation. These tools have been created with the objective of accurately reflecting the operation of the physical system, at high spatial and temporal resolution. As is the case with specialized models of physical systems, intelligent control is not reflected in these tools. Despite the existence of simulation tools for cyber aspects such as computing and communication, differences in temporal resolution and
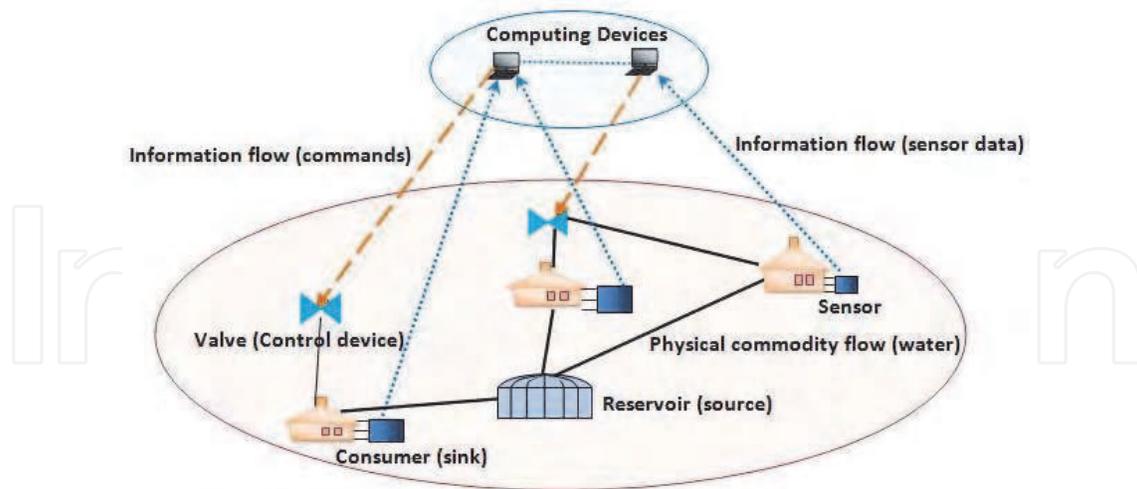
Fig. 1. An intelligent water distribution network.

data representation and the lack of well-defined interfaces pose considerable challenges to linking these simulation tools in a fashion that accurately represents the CPS as a whole.

In the first part of this chapter, we articulate the available simulation tools and the challenges present in integrated simulation of CPS, where the goal is to accurately reflect the operation and interaction of the cyber and physical networks that comprise the system. A solution is presented for the CPS domain of intelligent WDNs. The proposed solution utilizes EPANET to simulate the physical infrastructure of the water distribution network and Matlab to simulate the cyberinfrastructure providing decision support. Communication between the two simulators replicates the interactions between cyber and physical components of WDNs, and facilitates the observation of physical manifestations of intelligent control decisions. This communication between the simulators takes place without user intervention, as all information relevant to each simulator has been identified and extracted from the output of the other. Information flows from the physical simulator to the cyber simulator, replicating the operation of sensors in the physical infrastructure. The cyber simulator processes this data in Matlab, and provides decision support for water allocation, in the form of setting for control elements in the physical infrastructure. This information is provided to the physical simulator, which applies these settings. This process repeats for the duration of the simulation, as it would in the actual operation of a CPS.

The second part of this chapter addresses computation in the CPSs, specifically, the role of cyberinfrastructure in CPSs. We present an agent-based framework for intelligent environmental decision support. Due to the flexibility of software agents as autonomous and intelligent decision-making components, the agent-based computing paradigm is proposed for surmounting the challenges posed by a) fundamental differences in the operation of cyber and physical components, and b) significant interdependency among the cyber and physical components. The environmental management domain used as a model problem is water distribution, where the goal is allocation of water to different consuming entities, subject to the constraints of the physical infrastructure. In the cyber-physical approach to this problem, which is implemented by intelligent WDNs, the cyberinfrastructure uses data from the physical infrastructure to provide decision support for water allocation. We adopt *game theory* as the algorithmic technique used for agent-based decision support in an intelligent

WDN. In this initial effort, our focus is on providing decision support for the quantity of water allocated to each consuming entity. Game theory is a natural choice for complex resource allocation problems such as water distribution, where hydraulic and physical constraints, ethical concerns, and economic considerations should be represented. The investigation of game theory as the computational algorithm for water quantity allocation is assisted by Matlab, due to its powerful computational capability and ability to support advanced techniques, such as distributed decision support algorithms. EPANET provides the data used by the distributed computing algorithm to decide on water quantities.

In the third part of the chapter, we study the combination of game theory and the integrated cyber-physical simulator, and investigate how different configuration of actuators based on the game theory strategy can influence the malfunction of the purely physical WDN in the EPANET. When the faults are injected into the physical infrastructure (represented by EPANET) by setting certain combination of the actuators, we observe the effect on the operation of the WDN. This effort sheds light on how the advanced algorithm in cyber network can affect the purely water network through the integrated simulator and the limitation of using EPANET to simulate the possible failures on the WDN. Furthermore, the effort can validate the functionality that the game theory has in maintaining the equilibrium, and how the equilibrium is reached in the EPANET reflected by the change of values in node demand and flow level. The insight gained can be used to develop mitigation techniques that harden the WDN against failures, ensuring a return on the considerable investment made in adding cyberinfrastructure support to critical infrastructures.

Based on the completed work in the three parts, we conclude our contribution and present our plan of research in the future.

2. Related work

As public safety concerns and prohibitive cost necessitate the use of modeling and simulation for validation of intelligent environmental decision support systems (EDSSs), the utilization of EDSSs in managing critical infrastructure has been investigated in numerous studies. A general introduction to integrated decision support systems for environment planning is provided in Kainuma et al. (1990). Applications of EDSSs include prevention of soil salinization Xiao & Yimit (2008), regional environment risk management in municipal areas Wang & Cheng (2010), and environmental degradation monitoring Simoes et al. (2003). Examples particularly relevant to this book chapter are Xiao & Yimit (2008), which presents an integrated EDSS for water resource utilization and groundwater control; and Serment et al. (2006), which defines the major functionalities for an EDSS dedicated to the hydraulic management of the Camargue ecosystem. Discussion on available models and tools, such as GIS, and database management systems, is presented in Rennolls et al. (2004), which also presents an application of biogeochemical modeling for sustainability management of European forests.

Resource management algorithms have also been proposed for intelligent regulation. For instance, hedging rules have been utilized to minimize the impact of drought by effectively reducing the ongoing water supply to balance the target storage requirement Tu et al. (2003). Applications of game theory include optimization of rate control in video coding Ahmad & Luo (2006), allocation of power in frequency-selective unlicensed bands Xu et al. (2008), and power control in communications MacKenzie & Wicker (2001). Most relevant to this book

chapter is the use of game theory in analyzing water resources for optimal allocation Yu-Peng et al. (2006). Unlike our work, where the focus is to enable environmental management, specifically water allocation, through the use of CPSs; the focus of Yu-Peng et al. (2006) is on incorporating social and economic factors to provide a solution that maximizes the overall value of water resources while satisfying both administrative resources allocation mandates and consumer requirements.

This book chapter presents an EDSS, with the broader goal of applying the insights gained to similar CPSs. Many CPSs, especially critical infrastructure systems, can be viewed as commodity transport networks. WDNs are an example, as are smart grids and intelligent transportation systems. The commodity transported varies from one domain to another, but the systems share the goal of allocating limited resources under physical constraints, and leverage the intelligent decision support provided by cyber infrastructure in achieving this goal.

As an emerging research area, the body of literature specifically related to CPSs is limited. A considerable fraction of related work examines critical infrastructure systems. The focus of the majority of studies related to CPSs, e.g., Haimes & Jiang (2001); Pederson (2006); Rinaldi (2004); Svendsen & Wolthusen (2007) is on interdependencies among different components of critical infrastructure. A relatively comprehensive summary of modeling and simulation techniques for critical infrastructure systems, an important category of CPSs, is provided in Rinaldi (2004). Related challenges are enumerated in Pederson (2006), where system complexity is identified as the main impediment to accurate characterization of CPSs. Other challenges include the low probability of occurrence of critical events, differences in the time scales associated with these events, and the difficulty of gathering data needed for accurate modeling. Our work is one of few studies in the emerging field of CPSs to go beyond qualitative characterization of the system to quantitative analysis.

Several challenges to the development of a generic framework for the design, modeling, and simulation of CPSs are articulated in Kim & Mosse (2008). Features described as desirable for such a framework include the integration of existing simulation tools, software reusability, and graphical representation of the modeling and simulation environment. The work presented in this book chapter meets all these criteria.

The study most closely related to the work presented in this book chapter is Al-Hammouri et al. (2007), where a method is proposed for integration of the ns-2 network simulator with the Modelica framework, a modeling language for large-scale physical systems. The paper highlights the challenge of two-way synchronization of the simulators. The key difference between this study and our work is that we link to a specialized simulator capable of accurately representing the operation of the physical infrastructure, in this case a WDN, at high resolution. The WDN simulator, and other related simulation tools are described in the next section of this book chapter.

3. Simulation tools and integration challenges

Our approach to simulation of a CPS is based on the use of existing simulation tools for the cyber and physical networks, respectively. This choice is due to the powerful capabilities of specialized tools in representing their domain (cyber or physical), which allows the focus of our work to shift to accurate representation of the interactions between the cyber and physical networks.

3.1 Simulation tools for the physical infrastructure of WDNs

Several tools are available for simulation of the physical water distribution infrastructure. Examples include EPANET, which can capture both quantity and quality of water throughout a distribution network United States Environmental Protection Agency (2011a); RiverWeb, which is focused on river basin processes National Center for Supercomputing Applications (2011); Water Quality Analysis Simulation Program (WASP), which provides watershed, water quality, and hydrodynamic models United States Environmental Protection Agency (2011d). Also considered for our study was Waterspot, which simulates water treatment plants Dutch Ministry of Economics (2011); the Ground Water and Rainmaker Simulators United States Environmental Protection Agency (2011c), which is mainly a teaching tool; and the General Algebraic Modeling System (GAMS), which provides a high-level modeling system for the mathematical programming and optimization National Institute of Standards and Technology (2011).

Among these simulators, EPANET provides the most detailed representation, as it can capture the layout of a WDN and track the flow of water in each pipe, the pressure at each node, the depth of the water in each tank, and the concentration of a chemical substance throughout the network during a simulation period United States Environmental Protection Agency (2011a). The simulator is provided at no charge by the Environmental Protection Agency. The extensive capabilities, ease of use, and lack of licensing fees motivated the choice of EPANET as the simulator for the physical infrastructure of WDN in our study.

The most recent release, EPANET 2.0, was the version used. Objects in EPANET can be classified as nodes, links, map labels, time patterns, curves and controls. Each node can in turn be a junction, reservoir, or tank, and each link can be a pipe, pump, or valve. The topology depicted in Fig. 2 is a very simple WDN as visualized by EPANET. It is composed of one reservoir, one tank, one pump, one valve, five junctions, and several pipes that connect these elements. A reservoir is a node that represents an infinite external source or sink of water United States Environmental Protection Agency (2011b), and is used to model an entity such as a lake, river, or groundwater aquifer. A tank is a node with storage capacity, where the volume of stored water can vary with time during a simulation. A junction is a point in the network where links join together and where water enters or leaves the network. When a junction has negative demand, it indicates that water is entering the network at that point.

Pumps and valves are two primary actuators that can be turned on and off at preset times, or in response to certain conditions in the network. Fluids possess energy, and the total energy per unit weight associated with a fluid is denoted as "head." On many occasions, energy needs to be added to a hydraulic system to overcome elevation differences, or losses arising from friction or other factors. A pump is a device to which mechanical energy is applied and transferred to the water as total head, so it can add more energy to the fluid. The flow through a pump is unidirectional. If the system requires more head than the pump can produce, the pump is shut down. Therefore, pumps can be turned on and off at preset times, when tank levels fall below or above certain set-points, or when the pressure at a certain node falls below or above specified thresholds.

A valve is an element that can be opened or closed to different extents, to vary its resistance to flow, thereby controlling the movement of water through a pipe. The status of each valve can be specified for all or part of the simulation by using control statements. Pipes are links that convey water from one point in the network to another. The direction of water flow is from
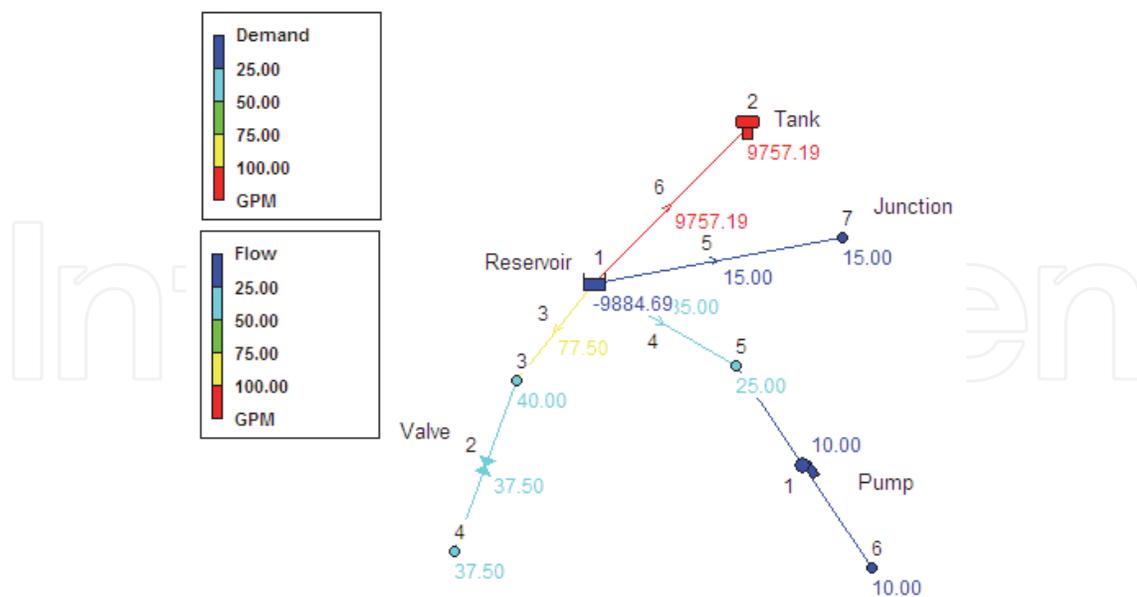
Fig. 2. A simple topology in EPANET

the end at higher hydraulic head to that at lower head, due to the effect of gravity. A negative label for a flow indicates that its direction opposes that of the pipe.

In the WDN depicted in Fig. 2, the reservoir is providing water to the tank and a number of different junctions. This topology can serve as a simple and abstract representation of a lake that provides water to consuming entities spread throughout a city. The reservoir in this figure always contributes water into the network, so its demand value is negative. The value of the demand indicates the amount of water contributed, in this case 9884.69 gallons per minute (GPM). The tank consumes the highest amount of water. Each junction is also labeled with its demand value, and each pipe with its flow speed. The entire graph is color-coded to simplify the categorization of demand or flow. The demand values of pumps and valves vary in accordance with the nodes they control.

A more complex topology is depicted in Fig. 3, which shows a screen capture at hour 8:00 of a 24-hour simulation period. This figure also depicts node groupings, circled in green, that can facilitate study of a subset of the nodes in the topology.

After simulating the system for the specified duration, EPANET can provide a report in graph, table, or text form. Among the various reports available, the full report provides the most comprehensive data, including the initial and updated values of all properties of the nodes and links within each simulation time step (one hour by default). The water flow, pressure at each node, depth of water in tanks and reservoirs, and concentration of chemical substances can be tracked from the recorded data. Figs. 4 and 5 present snapshots of the link and node information, respectively, of the full report.

3.2 Simulation tools for the cyber infrastructure of WDNs

Matlab R2010b was used to represent computational aspects of the CPS, due to its powerful mathematical tools and capability of supporting a diverse range of I/O formats, which is critical to successful interfacing to simulators for the physical and communication aspects. This version of Matlab provides support for parallel computing, which is essential for
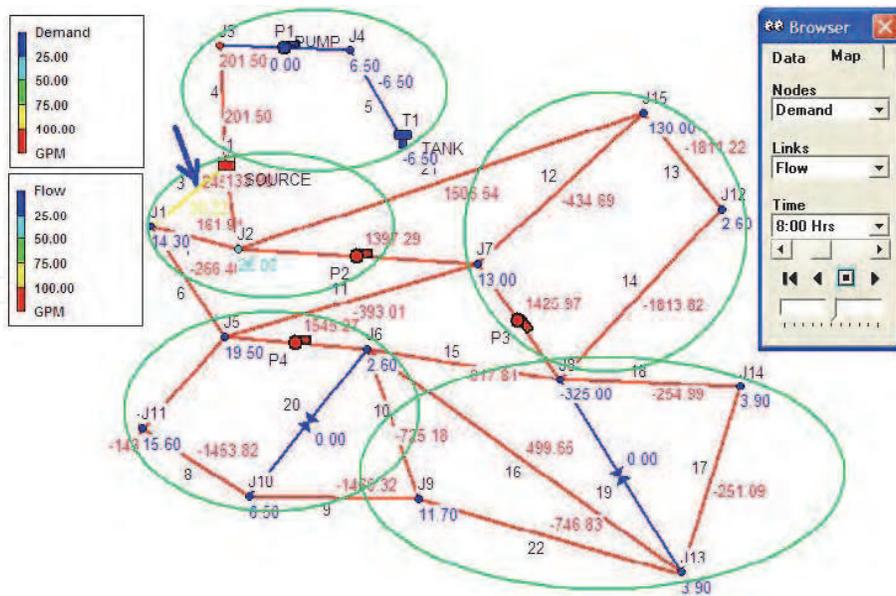
Fig. 3. A more complex topology and node groupings in EPANET

```
Link Results at 1:00 Hrs:
----------------------------------------------------
Link      Flow  VelocityUnit Headloss    Status
ID        GPM       fps       ft/Kft
----------------------------------------------------
1       135.65      0.28       0.05        Open
2        69.84      0.20       0.03        Open
3        34.66      0.22       0.06        Open
4        75.00      0.48       0.25        Open
5        -2.50      0.02       0.00        Open
6      -175.31      0.50       0.16        Open
7     -1364.58      3.87       7.33        Open
8     -1370.58      3.89       7.39        Open
```

Fig. 4. Link information from full report

```
Node Results at 1:00 Hrs:
----------------------------------------------------
Node   Demand        Head    Pressure   Quality
ID       GPM          ft        psi
----------------------------------------------------
J1        5.00     1000.29     173.45      0.00
J2       10.00     1000.15     260.04      0.00
J3       75.00      998.77     216.12      0.00
J4        2.50      833.99      58.06      0.00
J5        7.50     1000.46     216.85      0.00
J6        1.00     1024.65      97.34      0.00
J7        5.00     1001.11      87.14      0.00
J8     -100.00     1023.99     391.70      0.00
```

Fig. 5. Node information from full report

simulation of the cyber layer of a WDN, as the decision support algorithms used are typically implemented in a distributed fashion.

ns-2 USC Information Sciences Institute (2011), a public-domain discrete event simulator, is the tentative choice for representing the communication network, an aspect of the cyber infrastructure that is yet to be investigated.

3.3 Challenges in linking simulators for the cyber and physical networks

Accurate simulation of a CPS hinges on correctly recreating the information flow of Fig.1, through the following iterative procedure:

1. Simulating the operation of the physical infrastructure.

2. Extracting the data, e.g., water pressure in various pipes, required by the decision support algorithms from the report generated in Step 1, and converting this data to an acceptable input format for the simulator for the cyber infrastructure.

3. Simulating the operation of the cyber (computing) infrastructure, including the data of Step 2 as input. This data may be supplemented by other information, e.g., historical averages. The goal of this step is generation of settings for control elements, e.g., valves, in the physical layer.

4. Converting the output of Step 3 to a format acceptable as input by the simulator for the physical infrastructure.

5. Providing the data from Step 4 as input to the simulator for the physical infrastructure.

6. Repeat Step 1.

The procedure described above is repeated iteratively for the duration of the simulation. After the initial setup, all steps are expected to take place without user intervention, as would be the case with using a single simulator. As described in Section 1, differences in temporal resolution and data representation, and the lack of interoperability, especially in interfaces, pose considerable challenges in linking cyber and physical simulators in a fashion that accurately represents the CPS as a whole. Our approach to overcoming these challenges is discussed in Section 4, which describes the simulation of an intelligent WDN using Matlab and EPANET.

4. Integrated cyber-physical simulation of intelligent WDNs

One of the main contribution of this book chapter is in developing a procedure for simulation of an intelligent WDN, such that cyber (computing) and physical aspects of the CPS are accurately and precisely represented. As described in Section 3, Matlab and EPANET, respectively, are used to simulate the computing and physical infrastructures of an intelligent WDN. The procedure described in Section 3.3 is necessary, as it would be for a CPS from any other domain. Fig. 6 depicts this procedure for the specific case of simulation of an intelligent WDN with EPANET and Matlab. The numbers identify the corresponding step from the procedure described in Section 3.3.
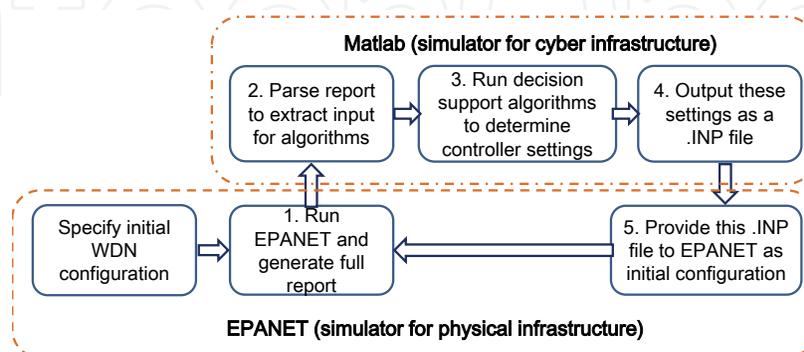

Fig. 6. Procedure for simulation of an intelligent WDN

The first step in simulating an intelligent WDN is to specify the duration to be simulated and the configuration of the physical infrastructure, e.g., topology and demand values, in

EPANET. A 24-hour duration was selected for the simulation presented in this section. After simulating the system for the specified duration, EPANET generates a full report that includes information for all links and nodes for each time step (one hour by default), as shown in Figs. 4 and 5. The full report generated as the output file of EPANET is automatically saved as a plain-text .NET file. This information includes values required as input by the decision support algorithms of the cyber infrastructure, which in turn determine settings for physical control elements such as valves.

To simulate the provision of sensor readings and other information about the physical infrastructure to the cyber control system, the full report generated as output by EPANET needs to be provided as input to Matlab. This necessitates pre-processing of the file, and parsing of the data into the matrix form required by Matlab. A script using the *textscan* and *cell2mat* commands can be defined within Matlab to carry out this pre-processing to generate a separate matrix from the EPANET data for each entity (node or link) for each simulation time step recorded in the full report, e.g., hour 1:00.

For simplicity, the simulation illustrated in this section was focused on node flow. The controller (pump or valve) settings were determined by averaging the node demand within a node group, which is a subset of nodes defined in EPANET. Fig. 3 shows a number of groups. The same parsing approach can be used to extract additional data, e.g., water pressure or concentration of a given chemical, from the EPANET report, as required by more sophisticated decision support algorithms.

Each node group can reflect an associated group of consumers, such as residential nodes in the south of a city. The only requirement is that each node group include at least one controller (pump or valve), so controller settings determined by the cyber infrastructure can be utilized in water allocation. The focus of the simulation in this section was integrated simulation of the CPS, and as such, a simplistic approach was taken to water allocation, with the goal of distributing the water as equitably as possible, subject to physical constraints on the nodes. More intelligent decision support can be achieved through game-theoretic approaches Yu-Peng Wang & Thian (2006), and it will be elaborated in Section 5.

Matlab generates a matrix of controller settings, which need to be provided to EPANET, as they would be to the physical control elements in an actual WDN. A .INP file is required, in a format identical to the original input provided to EPANET in the first step of the simulation, with controller values updated to reflect the settings determined by the decision support algorithm. A Matlab script utilizing the *dlmwrite* and *fprintf* commands can be used to generate a .INP file with the format expected by EPANET.

```
[TITLE]
EPANET INPUT FILE

[JUNCTIONS]
; ID     Elev     Demand     Pattern
1        600      5          1
2        400      -4.5       1
3        500      25         1
4        700      2.5        1
5        500      4.3        1
6        800      1          1
7        800      -19.5      1
8        120      -100       1
```

Fig. 7. EPANET input file generated by MATLAB

In the final stage of the simulation, the .INP file generated by Matlab, which specifies settings for various control elements, is used to initiate another execution of EPANET, closing the physical-cyber-physical loop. The process can be repeated as necessary to simulate operation of the WDN over multiple cycles of cyber control. Fig. 7 shows the file resulting from execution of the water allocation algorithm for the node groups of Fig. 3. The result of executing EPANET with the .INP file generated by Matlab is shown in Fig.8. As an example of the manifestation of cyber control, the flow in the link connecting Junction1 (J1) and SOURCE, marked with an arrow, has been reduced from 75-100 GPM (yellow) in Figure 3 to 50-75 GPM (green) in Figure 8.
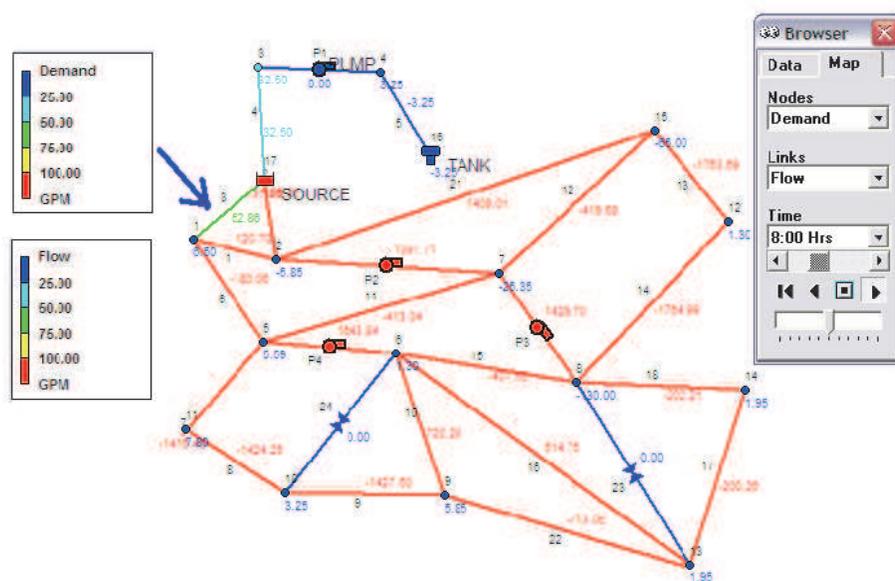

Fig. 8. Complex topology after applying cyber control

5. Intelligent water allocation as a game

In this section, we present an agent-based framework for intelligent environmental decision support. Among the techniques available for modeling intelligent environmental decision support systems (EDSSs), agent-based modeling holds particular promise in surmounting the challenges of representing both cyber and physical components, with high fidelity, in one system; and characterizing their interaction quantitatively. This is due to the capability of an agent-based model to encapsulate diverse component attributes within a single agent, while accurately capturing the interaction among autonomous, heterogeneous agents that share a common goal achieved in a distributed fashion. Sensors are key to this approach, as they provide situational awareness to the agents and enable them to function based on the semantics of their mission and the specifics of their environment.

The specific environmental management problem addressed in our work is water distribution, i.e., the allocation of water to different consuming entities by an intelligent WDN. The work presented in this section investigates the adoption of game theory as the algorithmic technique used for agent-based decision support in an intelligent WDN. The focus is on management of the quantity of water allocated to each consuming entity. Our proposed approach is based

on the utilization of game theory for resource sharing and service provision in peer-to-peer networks Gupta & Somani (2005).

5.1 Model of the service game

In this section, we model the interaction among selfish agents, the consuming entities, as a service game, using the notation of Gupta & Somani (2005), where the service game presented models resource sharing in peer-to-peer networks. We divide time, t, into discrete numbered slots, e.g., $t = 0$ or $t = 1$. During each time slot, each agent can receive requests for service from other agents, or request their services for itself. The service in question here is the provision of water. The quality of the water provided is beyond the scope of this book chapter; our focus is on quantity. The model presented in this book chapter is a first step that seeks to demonstrate the feasibility of an agent-based implementation of an EDSS based on game theory. In this preliminary model, we assume an unlimited water supply. This assumption is justified in cases where water resources are not scarce, and the aim of decision support is to facilitate more efficient water distribution. Future work will investigate the application of game theory to a WDN with limited water supply.

Each request issued by an agent can be sent to more than one service provider (peer agent), to increase the probability that the request will be fulfilled. For a service provider, the incoming requests can arrive either in parallel or in sequence. A request will stop propagating among the agents when any of the providers agree to serve, at which point the request is considered to have been fulfilled. For simplicity, we assume that an agent can submit only one service request and can accommodate only one service request during a time slot. An agent's status for a given time slot is labeled as $\{Srv\}$ if it fulfills any of the requests received during the time slot. The status of all agents and requests is propagated throughout the system. The cycle of service request and provision repeats indefinitely, which corresponds to an infinitely repeated game, G^∞, where the basic game being repeated is G.

More specifically, the basic game, G, is defined in terms of the following items:

- Players: all peer agents that participate in water allocation; for tractability, peer agents are assumed to be identical.

- Actions: each agent can decide for or against service provision, denoted as $\{Srv\}$ and $\{Dcln\}$, respectively.

- Preference of each player: represented by the expected value of a payoff function determined by the action taken. When service is received by an agent, the payoff value of the agent denoted as utility, U; when the agent provides service, the payoff value is denoted as cost, C.

The reputation of a player, i, in a given time slot, t, is denoted by $R(t, i)$, and depends on whether or not it provides service, both in the current time period and in prior periods, as represented by Equation 1:

$$R(t, i) = R(t - 1, i) * (1 - a) + (w * a), \ 0 \leq a \leq 1, t \geq 2 \tag{1}$$

If service is provided by player i in time period t, w is set to 1, otherwise 0. The reputation of all players is initialized as 0 at time $t = 0$, and is defined as w at $t = 1$. Therefore, $0 \leq R(t, i) \leq 1$ is always maintained. In Equation 1, parameter a is a constant that captures the strength of the "memory of the system," i.e., the relative importance of current vs. past behavior of an

agent in determining its reputation. The notion of reputation is key in the game model, as it affects the probability of receiving service for a player, and forms the incentive mechanism to contribute service in the system. More detailed discussion is presented in Section 6.

5.2 Nash equilibrium of the game

In this section, we investigate the Nash equilibrium action profile of the service game defined above. Per the Nash Folk theorem, investigating this equilibrium for a single iteration of the game G will suffice, as G^∞ will have the same equilibrium Fudenberg & Maskin (1986). The results of this section follow from the service game model, and as such, are based on Gupta & Somani (2005).

In the game model, the utility that a player gains increases with the player's contribution to the system, as the probability of receiving service is determined by the reputation of a player, which improves (increases) as the player provides service. Each player wants to gain the maximum benefit from the model, leading to a non-cooperative game. Nash equilibrium is reached when competition ends among the players. This occurs when the collective set of actions taken by the players with respect to service provision is locally optimum, i.e., no player can improve its utility by electing a different strategy. The two types of Nash equilibria are *Pure* and *Mixed*.

5.2.1 Pure Nash equilibrium

Pure Nash equilibrium results when every player declines to serve, i.e., elects the action $\{Dcln\}$. This is easily proven. If only one player, i, elects to serve, then its payoff is $-C$, as compared to the (higher) payoff of 0 that would result from declining to serve. Every other player has declined to serve, and as such the serving player, i, is unable to utilize its increased reputation to obtain service from others, discouraging further provision of service. This action profile leads to a stalemate, where no service is provided anywhere in the system, and as such is considered a trivial equilibrium.

The opposite case, where all players elect to serve is not a local optimum, and hence not a Nash equilibrium action profile. If every other player is providing service, then the best strategy for any single player is to decline service, resulting in a payoff of U instead of $U - C$.

5.2.2 Mixed Nash equilibrium

The agents responsible for decision support in a WDN are considered to be peers, and members of a homogeneous population, in terms of capabilities and responsibilities. As such, it is assumed that the Nash equilibrium reached will be symmetric, i.e., all players will choose the same strategy. This enables us to drop the player index i in referring to parameters in the discussion below.

The symmetric equilibrium action profile of interest is mixed-strategy, where players elect to serve in some time periods and decline service in others. As previously mentioned, the pure-strategy equilibrium of no service throughout the system is not a sustainable operational state for a WDN.

In the mixed-strategy symmetric Nash equilibrium action profile, each player, i, elects to serve with probability p and declines service with probability $1 - p$, with $p > 0$, meaning that either action is possible. We assume that each player can provide service prior to requesting it.

The expected payoff value of electing to serve during time period t is defined as:

$$\text{Payoff}(Srv) = p * (-C + R(t, Srv) * U) \tag{2}$$

In Equation 2, the term $(-C + R(t, Srv) * U)$ illustrates the tradeoff inherent to service provision, namely, that cost of providing service as compared to the benefit of receiving service. The term $R(t, Srv) * U$ reiterates that the probability of obtaining service in the current time period depends on a player's reputation. This payoff value of a player not only reflects its current payoff after providing service, but also captures the potential to obtain service in the next period, through the inclusion of $R(t, Srv)$, which can be used as a health indicator that reflects the capability of the player to gain service in the near future. When service is provided, $w = 1$, and per Equation 1:

$$R(t, i) = R(t - 1, i) * (1 - a) + a \tag{3}$$

Similarly, the payoff value of selecting the action $\{Dcln\}$ is:

$$\text{Payoff}(Dcln) = (1 - p) * (R(t, Dcln) * U) \tag{4}$$

The equation reflects the "no contribution, no cost" case. When service is declined, $w = 0$, and per Equation 1:

$$R(t, i) = R(t - 1, i) * (1 - a) \tag{5}$$

In a mixed-strategy Nash equilibrium of finite games, each player's expected payoff should be the same for all actions. In other words, the respective payoff values for $\{Srv\}$ and $\{Dcln\}$ are equal:

$$\text{Payoff}(Srv) = \text{Payoff}(Dcln) \tag{6}$$

Substituting from Equations 2 and 4 yields:

$$p * (-C + R(t, Srv) * U) = (1 - p) * (R(t, Dcln) * U) \tag{7}$$

Incorporating the iterative definition of reputation, from Equations 3 and 5, the probability of service provision, p, is determined as:

$$p = \frac{R(t - 1) * U(1 - a)}{-C + 2R(t - 1) * U(1 - a) + Ua} \tag{8}$$

Several noteworthy points arise from the equations above. Firstly, p changes during each time period, and is a function of the agent's reputation at the end of the immediately preceding period, $R(t - 1)$. Secondly, recall that this is a mixed-strategy Nash equilibrium action profile, where all players have the same p. Thirdly, we contend that this equilibrium is more stable than the pure-strategy equilibrium discussed above, as self-interest will motivate agents to eventually provide service in order to increase their chances of receiving service.

6. Design of experimental validation

In this section, we present experimental validation of the game-theoretic approach to water allocation described in the previous section. Matlab simulation was implemented with the three interacting peer agents shown in Fig. 9.
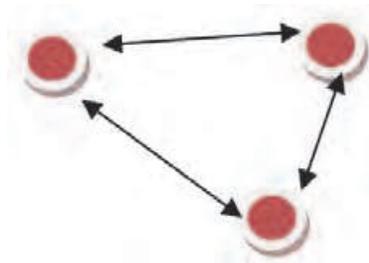
Fig. 9. Interaction among three peer agents.

The agents are labeled Node i, Node j, and Node k, respectively. For each agent, the service strategy is as shown in Table **??**. The strategy shown in Table **??** does not exhaustively capture all actions that could be taken by the three agents, but it provides a representative set of actions over a non-trivial duration of ten time slots.

Time t	Node i	Node j	Node k
1	Serve j	Serve k	Decline
2	Decline	Serve i	Decline
3	Serve k	Decline	Decline
4	Decline	Decline	Serve i
5	Serve k	Decline	Serve i
6	Serve j	Decline	Serve i
7	Serve j	Serve i	Decline
8	Decline	Decline	Decline
9	Decline	Decline	Serve j
10	Serve k	Serve i	Decline

Table 1. Strategy for service game.

According to the Table **??**, we can summarize the strategy of each player, i, as W_i below:

- $W_i = [1\ 0\ 1\ 0\ 1\ 1\ 1\ 0\ 0\ 1]$

- $W_j = [1\ 1\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ 1]$

- $W_k = [0\ 0\ 0\ 1\ 1\ 1\ 0\ 0\ 1\ 0]$

The configuration of initial values for the utility of obtaining service U and the cost of providing service C is $U/C = 80$, with $U = 800$ and $C = 10$. The main reason to adopt the ratio of utility to cost, $U/C = 80$, rather than their difference, $U - C$, is the normalization inherent to use of the ratio. In civil engineering literature, water pricing has been approached from a supply and demand perspective Brown & Rogers (2006); Cui-mei & Sui-qing (2009), which is what U and C try to capture.

The U/C ratio can reflect whether the water resource is scarce or sufficient. U/C is low when water is scarce, as serving a limited resource to other agents while maintaining sufficient resources for own usage purpose will be expensive for an agent, leading to high C; and gaining utility from other agents is difficult, leading to low U. Similarly, U/C is high when sufficient water exists for all peer agents. Our initial choice of $U/C = 80$ for the simulation reflects a non-draught situation. Simulation results for other values of U/C are presented in Lin et al. (2011, to appear).

7. Integration of game theory and Cyber-Physical Simulator

In this section, we apply the game theory in the cyber networks implemented by Matlab, which issues the control command to EPANET based on the computed result by equilibrium strategy. This is an effort to combine the game theory and the CPS simulator, which is expected to reflect the dynamic behavior of the CPS and reveal the interdependencies across the cyber-physical boundary.

7.1 The topology for the integrated simulation

The topology that we create for investigating the combination of game theory in Section5 and the integrated CPS simulator in Section4 is shown in Fig. 10. The principle that we follow to create this topology is to easy the application of game theory, which is applied on three agents to collaborate on water allocation.
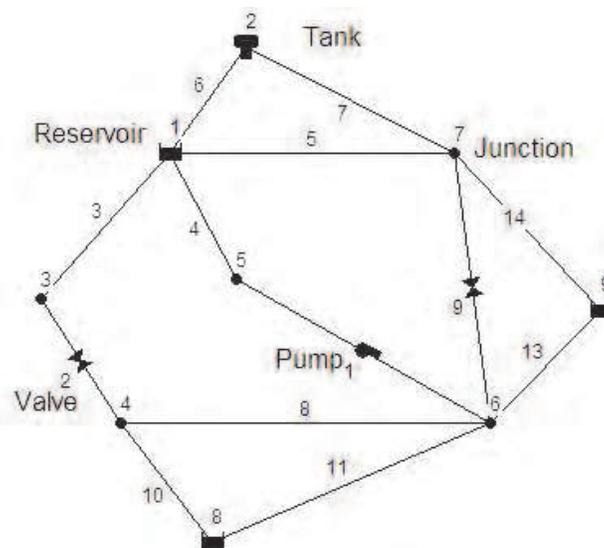

Fig. 10. Simple topology for integrating game theory.

The main criteria for creating the topology include two aspects: the water distribution network should have at least 3 actuators, either pump or valve, in charge of three different areas, respectively; the water distribution network should have 3 reservoirs, representing three agents to provide or retrieve water from their neighbors. Fig. 11 shows the grouped nodes in the topology, which indicates what components are incorporated in the scope managed by the particular agent. Each scope managed by one agent has one actuator.

7.2 Initial configuration

For the grouped components in Fig. 11, reservoir 1, tank 2, junction 5 and 7, pump 1 are in the same group; reservoir 8, valve 2, junction 3 and 4 are in the same group; reservoir 9, junction 6 and valve 9 are in the same group. After running EPANET as introduced in Fig. 6, the simulation results in the first hour (the time step that we configure for simulation is 1 hour) are summarized in Fig. 12 and Fig. 13.

Fig. 11 is a snapshot of the node demand in EPANET simulation at 1 hour, and from the result we can tell that at 1 hour, reservoir 1 is providing water (indicated by the negative demand value) and reservoir 8 and reservoir 9 are retrieving water (indicated by the positive demand value). Similarly as in the game theory experimental validation in Section6, we use 1
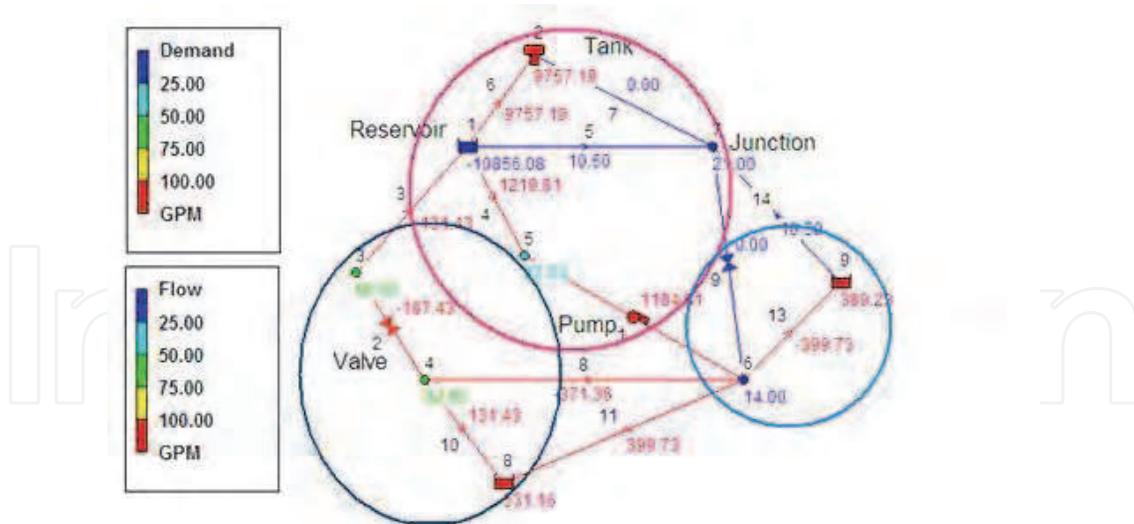
Fig. 11. Grouped nodes in the topology.

Fig. 12. Node demand (in GPM) at 1 hour.

to represent the state of serving water in one agent and 0 to represent the state of declining to serve water (including retrieving water from other agents). Accordingly, in the first simulation period, the script played by three agents is (1, 0, 0). Similarly as shown in the topology of Fig. 9, we suppose the reservoir 1 is node i, and reservoir 8 and 9 are node j and node k, respectively.

In terms of implementation, the water attributes (demand, pressure, head, flow, etc.) in EPANET are controlled by the actuators (pump and valve). By sending the control command to the actuator from the cyber infrastructure (implemented in MATLAB), we can configure the serve/decline to serve operation of the node (reservoir). Because there are three actuators in Fig. 11 with the open/close options, we can have totally 8 different combinations, shown in Fig. 14.

The initial configuration (constraints) of the components (pump, valve, tank, node) can affect the simulation result, and we set the initial values as following:

Link ID	Flow GPM	Velocity fps	Unit Headloss ft/Kft	Status
Pipe 3	-37.80	0.11	0.01	Open
Pipe 4	35.00	0.10	0.01	Open
Pipe 5	16.97	0.05	0.00	Open
Pipe 6	9757.19	27.68	280.00	Open
Pipe 7	0.00	0.00	0.00	Closed
Pipe 8	-32.90	0.09	0.01	Open
Pipe 10	-37.80	0.11	0.01	Open
Pipe 11	-16.97	0.05	0.00	Open
Pipe 13	16.97	0.05	0.00	Open
Pipe 14	16.97	0.05	0.00	Open
Pump 1	0.00	0.00	0.00	Closed
Valve 2	-18.20	0.05	0.00	Open
Valve 9	12.95	0.04	0.00	Open

Network Table - Links at 1:00 Hrs

Fig. 13. Flow in the link (in GPM) at 1 hour.

Reservoir	1	8	9	Result at the 0:00 hr
Actuator	Pump 1	Valve 2	Valve 9	
Status of actuator	Open	Open	Open	Error. Pump 1 open but exceeds max flow at 0:00 hr.
	Open	Open	Close	Reservoir 1 is serving, others are not. (1, 0 , 0)
	Open	Close	Open	Error. Pump 1 open but exceeds max flow at 0:00 hr.
	Close	Open	Open	All the three reservoirs are serving at 0:00 hr. (1, 1, 1)
	Close	Close	Open	All the three reservoirs are serving at 0:00 hr. (1, 1, 1)
	Close	Open	Close	All the three reservoirs are serving at 0:00 hr. (1, 1, 1)
	Open	Close	Close	Reservoir 1 and 9 are serving, reservoir 8 is not. (1, 0, 1)
	Close	Close	Close	All the three reservoirs are serving at 0:00 hr. (1, 1, 1)

Fig. 14. Result at 0:00 hr with different configuration of actuators.

- All the three reservoirs (1, 8 and 9) have the total head of 1000 feet and elevation of 1000 feet.

- Valve 2 has 12 inch diameter, the type is PRV, loss coefficient is 0, and the fixed status is set as none, as it can be open or closed.

- Pump 1 has pump curve 1 and the initial status is set as open.

- Valve 9 has 12 inch diameter, the type is PRV, loss coefficient is 0, and the fixed status is set as none, as it can be open or closed.

- Tank 2 has elevation of 10 feet(the elevation above a common datum in feet of the bottom shell of the tank) of 700 feet, initial level (the height of the water surface above the bottom elevation of the tank at the start of the simulation), minimum level of 0 feet(the minimum height in feet of the water surface above the bottom elevation that will be maintained; the tank should not be allowed to drop below this level), maximum level of 20 feet (the maximum height in feet of the water surface above the bottom elevation that will be maintained; the tank should not be allowed to rise above this level) and 50 inch diameter.

- Junction 3 has elevation of 700 feet, base demand of 80 gpm, and its actual demand is shown during simulation.

- Junction 4 has elevation of 500 feet, base demand of 75 gpm, and its actual demand is shown during simulation.

- Junction 5 has elevation of 600 feet, base demand of 50 gpm, and its actual demand is shown during simulation.

- Junction 6 has elevation of 500 feet, base demand of 20 gpm, and its actual demand is shown during simulation.

- Junction 7 has elevation of 600 feet, base demand of 30 gpm, and its actual demand is shown during simulation.

Subjected to the limited cases that actuators can manipulate the water flow and the constraints of the capacity of pipe and node, such as the maximum flow the pipe can sustain for pump 1, when we use the game theory to control the water resource on the EPANET, we need to take these constraint factors into consideration and make decision accordingly.

Indicated by Fig. 14, we should avoid the failures generated by the two types of configuration of the actuators. In another words, EPANET can not continue the simulation if pump 1, valve 2 and valve 9 are in the status of (open, open, open) or (open, close, open). This shows that the command issued from the cyber simulator for controlling the actuators can lead to the errors or malfunction of the underlying simulator for the physical network, and in this case, it is EPANET.

According to Fig. 14, three patterns (strategy of the player) of water resource provision are repeated consecutively, and they are (1, 0, 0), (1, 1, 1) and (1, 0, 1). We define the pattern as serving pattern and the serving strategy similarly as Table **??** is the combination of the three patterns. For example, if the initial serving pattern is (1, 0 ,0), the we configure the next serving pattern as (1, 1, 1). There are multiple actuator setting methods to achieve this serving pattern, for this case, we select the combination of (close, open, open), mapping with pump 1, valve 2 and valve9. All the rest of the configuration remains the same as initial configuration. The generated control command file (input .INP file to EPANET) by MATLAB is shown in the snapshot of as Fig. 15, which captures the part of actuator configuration. As shown in the .INP file, the three actuators are configured as (close, open, open).

```
[TAGS]

[DEMANDS]
;Junction                    Demand

[STATUS]
;ID                          Status/Setting
 1                           Closed
 2                           Open
 9                           Open
```

Fig. 15. The configuration for actuator in .INP file.

7.3 Result and analysis

The topology in Fig. 16 shows the simulation result after actuators are configured as (close, open, open), which leads to the scenario that all reservoirs are serving. In Fig. 16, all the serving reservoirs are indicated by blue color with negative value of demand in GPM.
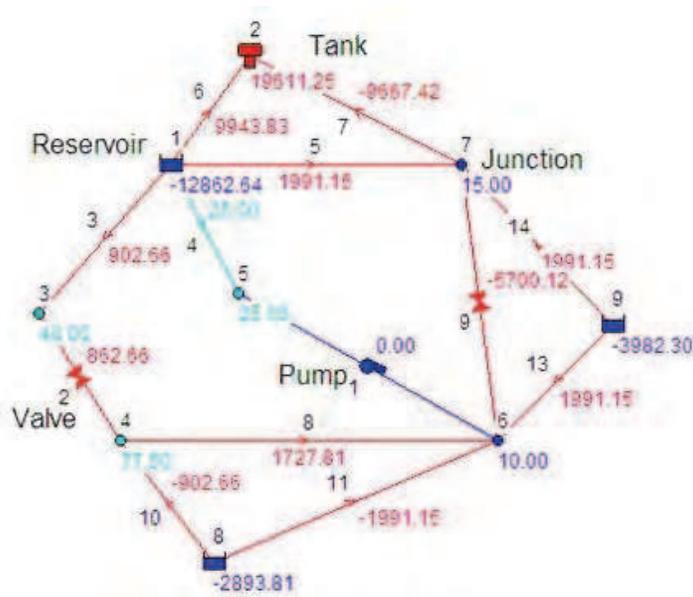

Fig. 16. Topology of simulation for all reservoirs are serving.

After we run EPANET based on the configuration set in MATLAB, the simulation results in the very first hour (0:00 hr) are presented as Fig. 17 and Fig. 18.

We further investigate the case that three reservoirs are consistently providing water, i.e. throughout the total 10 simulation periods, all the three reservoirs are always providing water. Fig. 19 summarizes the demand values (in GPM) of each reservoir in time series.

Given the current initial configuration, the EPANET can run successfully and can generate the simulation values for each reservoir provided above. At time 0:00hr, all the reservoirs are providing water, but the water quantity provided by reservoir 1 is much higher than the quantity provided by reservoir 8 and 9. Since 1:00 hr, the water quantity provided by reservoir 8 and 9 have dramatically decreased, whereas the majority of water is provided by reservoir 1. The simulation results gain some insights of the role that the advanced algorithm play and show some limitations of the integrated simulation, which are summarized as following:

1. The EPANET simulator, or the physical water network in real world, has certain capability to regulate water by itself to achieve stable status without cyber control or manipulation. Some other factors can play role in achieving the stable status, such as gravity.

Network Table - Nodes at 0:00 Hrs

Node ID	Demand GPM	Head ft	Pressure psi
Junc 3	40.00	996.59	128.51
Junc 4	37.50	996.59	215.17
Junc 5	25.00	1000.00	173.32
Junc 6	10.00	985.25	210.26
Junc 7	15.00	985.25	166.93
Resvr 1	-12862.64	1000.00	0.00
Resvr 8	-2893.81	1000.00	0.00
Resvr 9	-3982.30	1000.00	0.00
Tank 2	19611.25	710.00	4.33

Fig. 17. Node demand (in GPM) at 0 hour when all three reservoirs are serving.

Network Table - Links at 0:00 Hrs

Link ID	Flow GPM	Velocity fps	Unit Headloss	Status
Pipe 3	902.66	2.56	3.41	Open
Pipe 4	25.00	0.07	0.00	Open
Pipe 5	1991.15	5.65	14.75	Open
Pipe 6	9943.83	28.21	290.00	Open
Pipe 7	-9667.42	27.42	275.25	Open
Pipe 8	1727.81	4.90	11.34	Open
Pipe 10	-902.66	2.56	3.41	Open
Pipe 11	-1991.15	5.65	14.75	Open
Pipe 13	1991.15	5.65	14.75	Open
Pipe 14	1991.15	5.65	14.75	Open
Pump 1	0.00	0.00	0.00	Closed
Valve 2	862.66	2.45	0.00	Open
Valve 9	-5700.12	16.17	0.00	Open

Fig. 18. Flow in the link (in GPM) at 0 hour when all three reservoirs are serving.

Time Series Table - Node 1 / Node 8 / Node 9

Time Hours	Demand GPM	Head ft	Time Hours	Demand GPM	Head ft	Time Hours	Demand GPM	Head ft
0:00	-12862.64	1000.00	0:00	-2893.81	1000.00	0:00	-3982.30	1000.00
1:00	-9846.97	1000.00	1:00	-54.78	1000.00	1:00	-33.95	1000.00
2:00	-9911.10	1000.00	2:00	-93.90	1000.00	2:00	-58.20	1000.00
3:00	-9872.62	1000.00	3:00	-70.43	1000.00	3:00	-43.65	1000.00
4:00	-9821.32	1000.00	4:00	-39.13	1000.00	4:00	-24.25	1000.00
5:00	-9846.97	1000.00	5:00	-54.78	1000.00	5:00	-33.95	1000.00
6:00	-9911.10	1000.00	6:00	-93.90	1000.00	6:00	-58.20	1000.00
7:00	-9872.62	1000.00	7:00	-70.43	1000.00	7:00	-43.65	1000.00
8:00	-9821.32	1000.00	8:00	-39.13	1000.00	8:00	-24.25	1000.00
9:00	-9846.97	1000.00	9:00	-54.78	1000.00	9:00	-33.95	1000.00
10:00	-9911.10	1000.00	10:00	-93.90	1000.00	10:00	-58.20	1000.00

Fig. 19. Demand value changes in reservoir 1, 8 and 9.

2. The reservoir in EPANET has the ability to provide infinite quantity of water, which could be infeasible in real application case.

3. Although all the three reservoirs are providing water, the magnitude of provided water quantity is different. Compared with reservoir 1, the water provided by reservoir 8 and

9 can almost be neglected, although at the beginning reservoir 8 and 9 are providing more quantity of water. This change actually indicates the condition for reaching the equilibrium in a water distribution network, i.e. the case that all the reservoirs (or players) are consistently providing water is not an equilibrium or stable case, which conforms to our previous analysis in subsection 5.2.1 on the pure equilibrium case.

4. The game theory in MATLAB is an supplemental intelligence onto the EPANET, and it is an artificial manipulation for controlling the water rather than the hydraulic or physic law. The purpose to define the reputation of player and the expected payoff value is to investigate how the incentive mechanism for contributing service in the system can affect the equilibrium in the water allocation. The more the player serves, the higher reputation it can gain, and the higher probability it can gain water from other players. The parameters in the game theory configure how the game will play among the players, such as the probability that one player will serve in the next phase, but the strategy for service game played among the players (i.e. which player serve and which player decline to serve) determines the actual water allocation. In the combination of game theory and the integrated CPS simulator, we directly use the strategy played among the players, and set the configuration of actuators accordingly.

The effort of combining the CPS simulator and game theory shows the chain effect that the advanced algorithm can issue a command of controlling the actuator, and the configuration of the actuator can affect the simulation on the physical network. Sometimes the configuration of the actuators may cause failures as indicated in Fig. 14, and this is due to the fact that the physical components, such as pipes or tanks are subjected to the constraints which are configured initially. The simulation reveals the risk that in real application, the calculated configuration of the actuators can lead to the malfunctions of physical components, because of the multiple constraints exerted on the components. This discovery can be used to develop mitigation techniques that harden the WDN against failures, specifically, the design of advanced computing algorithm on the cyber network needs to consider the multiple constrains in the physical network, in order to ensure that adding the cyberinfrastructure to support the operation of critical infrastructure will not bring serious reliability issues.

8. Conclusion and future work

The CPSs are an recently emerging research area that incorporates the physical infrastructure and the cyber networks together. The simulation of the complicated system is the preliminary step towards assessing the impact that cyber control brings to the existing infrastructure system. However, the tools for their modeling and simulation are very limited. A number of related challenges were discussed in this book chapter, with focus on integrated simulation of CPSs, where the goal is to accurately reflect the operation and interaction of the cyber and physical networks that comprise the system, and reflects the interdependencies between the physical and cyber infrastructures. In this book chapter, we address one of the major challenges that is to accurately and precisely represent the features and operation of the physical infrastructure by adopting the domain-specific tool EPANET, a simulator for WDNs. A method was described and illustrated for using Matlab and EPANET in integrated simulation of intelligent WDNs, which make use of intelligent decision support to control the quantity and quality of water.

To quantitatively analyze the distribution of water quantity, we investigate the sophisticated algorithm, game theory, as the intelligent decision support facilitated by CPSs to revolutionize environmental management. An agent-based EDSS was presented that utilized game theory for allocation of water among consuming entities. The design of experiment was proposed to validate the model. Based on the created integrated simulator, we apply the game theory in the cyber networks for making decision to control the actuators on the physical network represented in EPANET. The result shows some of the limitation of the simulator, and what is more important, it reveals that if the decision support algorithms do not consider the constraints of the physical components (such as the maximum flow that pipe can sustain or tank capacity), the control command sent to the actuators can lead to the failures on the physical network. The combination effort reflects the interdependencies between the physical and cyber infrastructures that comprise a CPS. Understanding these interdependencies is a critical precursor to any investigation of CPS, especially with respect to reliability, and can be used to develop mitigation techniques to prevent failures caused by improper design of decision support algorithms.

The integrated simulation technique presented in this book chapter is a preliminary step that will facilitate further research towards CPS-based simulation and environmental decision support. Insights gained from the WDN domain will be used to extend the models and simulation techniques developed to other CPS domains, with the ultimate goal of creating CPS models that are broadly applicable, yet capable of accurately reflecting attributes specific to each physical domain. Future extensions to this work will involve refinements to the game-theoretic algorithm, incorporating sensor data into the decision support and taking the various constraints of physical components into consideration. The multi-objective optimization issue will be investigated in such case.
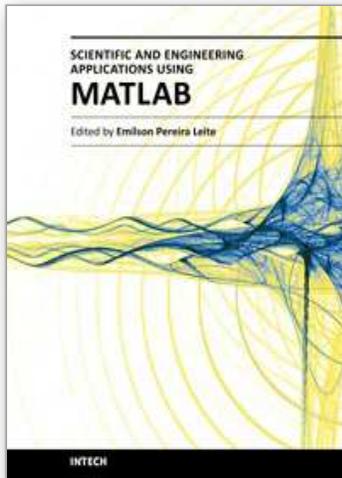
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The purpose of this book is to present 10 scientific and engineering works whose numerical and graphical analysis were all constructed using the power of MATLAB® tools. The first five chapters of this book show applications in seismology, meteorology and natural environment. Chapters 6 and 7 focus on modeling and simulation of Water Distribution Networks. Simulation was also applied to study wide area protection for interconnected power grids (Chapter 8) and performance of conical antennas (Chapter 9). The last chapter deals with depth positioning of underwater robot vehicles. Therefore, this book is a collection of interesting examples of where this computational package can be applied.

How to reference

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Jing Lin and Sahra Sedigh and Ann Miller (2011). Integrated Cyber-Physical Simulation of Intelligent Water Distribution Networks, Scientific and Engineering Applications Using MATLAB, Prof. Emilson Pereira Leite (Ed.), ISBN: 978-953-307-659-1, InTech, Available from: http://www.intechopen.com/books/scientific-and-engineering-applications-using-matlab/integrated-cyber-physical-simulation-of-intelligent-water-distribution-networks

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