Background
Most modern electronic devices rely on computing and communication to deliver their functionality in a flexible and cost-effective manner. However, in contrast with large enterprises that employ the Internet to integrate resources that often span the world, devices located in the same office, home, or factory floor operate all too often in total isolation. This gap makes it impossible to develop general-purpose flexible applications that engage available devices into the creation of a unified environment that is tailored to the needs of a specific individual or activity. The fundamental limiting factors are the inability of devices to communicate meaningfully with each other and the difficulty of developing applications that span multiple highly specialized devices. An important creative outlet is thus held in check, enormous economic opportunities are being squandered, and important societal benefits are being postponed. Many needs (from enhanced entertainment to home care for the elderly and the disabled) remain unmet because current approaches are overly complex and prohibitively expensive. The vision of ubiquitous computing remains just that, a long-term vision.

Premise
A realignment of technological capabilities and market forces is needed in order to make progress. The key to accomplishing this is to leverage off the revolution that is taking place in wireless technology. If we assume that every device in the home is equipped with a wireless interface it becomes possible to envision applications that cut across devices and integrate their functionality in novel ways. Opening up devices through a wireless interface needs to be coupled with strong security and safety mechanisms that provide adequate protection to manufacturers and consumers alike. Established encryption and key distribution techniques are already in use with exiting wireless devices such as wireless routers, mobile phones, etc., and can be readily extended for use with all devices in a given spatially constrained environment. Model checking and related formal models can provide strong guarantees that no conceivable applications can violate the integrity of the device. Starting with the premise that devices can be augmented to support limited code execution and to communicate via a standard wireless interface, we focus on the development of design techniques and middleware that will reduce significantly both the entry point into the market and the cost of competing applications.

Aspirations
Our ultimate goal is to create a new world market for applications targeted to the home, office, factory, hospital, and even military settings. This is not unlike the Apps market created by the iPhone. We envision a customer buying “open” devices without any concern as to how they will be integrated in the target environment. An open device joins a local wireless ad hoc network simply by being provided with a shared key—no additional setup steps, installation CDs, software upgrades, or Internet connectivity being needed. In the absence of any applications being executed over the ad hoc network, each device carries out its designed functionality independently of any other devices in the same environment.

A customer may enhance the overall functionality of a given environment simply by visiting a specialized applications store on the web. He/she can select a particular application based on the target environment, desired purpose, and device requirements. Once downloaded, the application is installed over the ad hoc network with no effort on the part of the customer. If the laptop or phone on which the application was downloaded is an authorized member of the network, an application specific key is automatically generated and the application code is distributed across the existing devices in accordance with the deployment rules built into the application specification. In some cases, the deployment rules may entail offering the customer choices through a simple dialog.

Application development is simplified by an open source coordination middleware specifically designed to facilitate rapid design of robust and trusted applications over ad hoc networks. The middleware will
leverage off the reflective properties of devices, i.e., the ability to self-describe the services they provide. Interactions among devices will be captured by specialized connectors, which will facilitate the transfer of data and events among devices, both pair wise or using more complex distribution patterns. Many connectors will be readily available as part of the middleware library while others will be custom designed by individual developers. Most applications will be constructed by simply specifying a set of connector deployment rules designed to accommodate dynamic changes in the configuration of the ad hoc network and the availability of devices. Virtual devices can also be included in the application in order to provide specialized user interfaces or to augment the overall functional capabilities of the application. They appear to the middleware and the associated application as indistinguishable from the physical devices, but they have no interfaces with the physical world and can be added and removed as applications are deployed or dropped. They can be local to a particular application or can serve as shared resources among otherwise independent applications.

**Illustrative Examples**

*Clock Synchronization:* Throughout the home, many devices have visible clocks. Loss of power and the daylight saving time often require manual adjustments. The presence of even a single device with access the atomic clock makes it possible to deploy an application that updates all clocks around the home. In fact, most devices have a display showing the time of day only because they need to allow the consumer to set the clock. With clock synchronization being automatic device interfaces can be simplified and reductions in production costs becomes feasible.

*Wireless Thermostat:* Current thermostats measure temperature, support user programmability, and control the HVAC system. One can easily envision decoupling the temperature sensor from the other functions. This allows for multiple temperature sensors to be placed inside and outside the home. By further separating the control logic from the HVAC function and from sensing, increasingly sophisticated control applications can enter the market. The simplest one mimics the current thermostat control; the application includes a simple virtual device, which provides the programming logic and controls, and connectors that provide access to a clock, the sensors around the home, and the HVAC electronics. Competing applications may aggregate temperature information from multiple sensors located inside and outside the home; may try to learn on the fly about the ideal temperature settings at different times of the day and make automatic adjustments with no programming; may take advantage of adjustable vents and activity detection sensors to optimize the temperature distribution across the entire home. Opportunities for energy conservation and optimized comfort levels are enormous and likely to stimulate the marketing of both novel low cost devices and applications.

*Fluid Entertainment:* The entertainment systems on the market today are highly proprietary, expensive, and inflexible. Conceptually simple functions are difficult to provide, integration among components from different manufacturers is complicated and rigid, controls are counterintuitive and hard to customize, multiple remotes are required, etc. Consider, for instance, the simple problem of having a pair of speakers in every room and piping the music from a selected sound source (e.g., radio) only to rooms in which someone is present (Figure 1). The most basic application creates a dedicated wireless distribution network from the radio to all the speakers in the home; each speaker knows its own assignment (left or right) and filters the sound stream appropriately; volume level is communicated with the stream; inexpensive motion or infrared detectors enable and disable the co-located speakers. The entire entertainment system along with the application can be deployed effortlessly in a matter of minutes. Using this as a starting point, the home may be enriched with new devices such as multiple CD players. If properly designed, the application will continue to function, but the opportunity is created to consider more sophisticated applications that allow multiple people to listen to different sound tracks as they move through the home, change music sources, or control the CD player remotely.
Elder Care: Faced with a growing aging population and skyrocketing health care costs, new and innovative strategies are being evaluated to help ensure the safety and well being of elderly relatives while allowing them to live nearly normal lives in a home setting. Special experimental facilities have been constructed to research different technical solutions, which are not likely to enter the market soon because are exorbitantly expensive. The approach we are advocating makes it possible to create in a very short time a market in which specialized applications target various levels of assistance or different dimensions of the overall problem in a natural and cost effective way. Somewhat intrusive, video monitoring of a mother’s activities by her daughter could be accomplished with several wireless cameras that include motion detection capabilities using a simple virtual device that controls which camera feed is used at any point in time. Later on, an application can be added to generate an alarm when a fall is detected and to save the last few minutes of video preceding the fall. Other applications can be deployed to monitor safe use of kitchen devices; to ensure that the proper medication is taken according to schedule; or to control the lighting at night—night time bathroom visits are one of the most common situations in which older people suffer broken hips. Ultimately, the range of applications can grow without bounds.

While it is easy to claim that all these applications can be developed today, there is no approach that offers the level of flexibility and the low development cost made possible by our integration of a coordination-centered middleware that uses open devices across a local ad hoc network.

Technical Challenges
From a marketing point of view the greatest challenge is to encourage device manufacturers to start producing open devices. This can be overcome initially by targeting a niche market with high consumer appeal. The first step towards this goal is to build an impressive demonstration system that shows how the key technical challenges can be overcome.
Open Devices. Building devices that can participate in the execution of applications over an ad hoc network is neither complicated nor costly. First, it demands the availability of a wired communication port such as the USB interface, which is readily available and already part of many devices on the market. Second, it requires giving selective access to state and controls associated with the device. One can ensure that such an interface is tamper-proof by design, e.g., by guaranteeing that software executing inside the device cannot be modified in any way and that the device state cannot be corrupted by outside agents because all control requests leading to state changes are ultimately filtered and executed by the software on the devices itself. This protects the device against errors and malicious actions at the application level, but not against design errors that would allow the device to enter an undesirable state. The latter needs to be addressed by proper use of formal methods. If the interface is kept simple and the designer has a good understanding of what integrity means for the particular device, verification can be carried out at design time. Finally, the interface should be reflective in order to allow new devices to enter the market without modifications to it or to other components of the overall system.

Coordination Stubs (Cubs). Under these design assumptions, the coordination middleware itself is treated as external to the device. Thus, vulnerabilities in the middleware do not transfer to the device itself. We envision the coordination middleware residing on a specialized low profile and low-cost physical (mote level) component, called a coordination stub. Each stub has two physical interfaces, a wired one to the device (e.g., USB) and a wireless one (e.g., Wi-Fi) to form the ad hoc network. The wired interface is the one used at initial configuration to associate a shared key among all coordination stubs in the environment. Cost is probably one to the most important considerations in the design of the stubs as one is required per device. Ultimately, the coordination stubs can be integrated in the device itself as long as reasonable software or hardware decoupling is preserved in order to ensure the same level of security and integrity.

Coordination Middleware. The principal responsibilities associated with the coordination middleware are security, local device access, communication, and application support (deployment, redeployment, and execution).

- The integrity of the ad hoc network is ensured by requiring all coordination stubs to share a single key, which is received before the stub is physically connected to any devices in the environment; all communication is encrypted using this key and no device can join the network without having the shared key. In addition, components of the same application share their own key, which is assigned automatically when the application is first deployed.
- Access to the local device is ensured by the reflective nature of its interface. High-level information about the device is shared among coordination stubs in order to enable proper application deployment. State information and control commands are used by application components that make use of each device.
- Communication protocols are involved in establishing the ad hoc network and in supporting routing of messages, which may be associated with the coordination process or with specific applications.
- Application deployment and redeployment is controlled by the availability of devices and the deployment rules provided by the application. These rules may require the installation of code to support virtual devices and connectors among physical and virtual devices. The rules are executed by the coordination middleware, which is also responsible for making adjustments in response to application events and configuration changes. Most of the activities associated with the execution of the application entail support for the semantics of the connectors and optimization of their operations.

Wireless Applications (Wi-Apps). Development of a wireless distributed application is centered on the design of a set of deployment rules that specify the types of devices required by the application and the set of connectors that tie the devices together in order to achieve the desired functionality. The declarative style of the specification and the use of open source connectors simplify program development. While the most sophisticated applications may require the construction of new specialized connectors or virtual devices, many useful applications are likely to consist simply of a set of deployment rules. We anticipate that many applications, virtual devices, and components will be readily available as part of an open source repository with applications being marketed through an on-line store.
- **Connectors.** A connector may have multiple endpoints. The exact number can be static or dynamic, i.e., determined by the context in which it is used and subject to evolution over time. A multicast connector falls in the latter category. Each endpoint specifies the type of device interface with which the connector is compatible—the nature of the specification can vary from being purely syntactic to including semantic and even quality of service considerations. The connector behavior is associated mostly with data transfer, but the logic may be complex, e.g., it may include data integration, data exchange protocols, synchronization, failure signaling, and data conversion plug-ins. For the sake of simplicity, the connector code acts as if the connector were static and delegates to the deployment rules all changes involving the configuration of endpoints and the binding to devices. The code of the connector is actually distributed and mobile across the stubs hosting the endpoints and takes advantage of the data and code transport facilities provided by the coordination middleware.

- **Virtual devices.** For applications that demand specialized computations or require user interfaces over standard compute/display platforms (e.g., mobile phone), virtual devices offer a uniform architectural treatment of all components across the application. They are designed to expose (for binding to connectors) the same kind of interface as the physical devices in the environment while their body may contain arbitrary code, i.e., may make use of coordination middleware capabilities or software specific to the particular platform. As with connectors, the placement of virtual devices over stubs is delegated to the deployment rules.

- **Deployment rules.** The deployment (and redeployment) rules define the relation between the physical world of devices and the application being deployed to control and exploit them. The rules are interpreted by the coordination middleware and are applied in a context sensitive way. In principle, the coordination middleware acquires a global view of the state of the ad hoc network and uses it to determine the placement of virtual devices and the binding of connectors to devices. As the network configuration changes or exceptions are raised at the application level, rules get reapplied with placements and bindings being altered accordingly. A great deal of flexibility is needed in order to accommodate a wide range of dynamics. The set of available devices can change rapidly, multiple applications may coexist at different times, multiple users may enter and leave the scene, electromagnetic interference may affect the availability and quality of the wireless links, etc. As the middleware evolves, there is an opportunity to refine the implementation of deployment rules in order to optimize various utility metrics.

Finally, it is of paramount importance to treat wireless applications as consumer products. Clever ways must be found to allow consumers examining entries in the store to understand the device requirements associated with each application and the behavior it can deliver. Offering applications on a trial basis at no cost to the consumer will be useful and likely to increase sales and promote public trust. However, cost, performance, utility, and predictability will be the ultimate key to success.

**Conclusions**

Our ultimate goal is that of empowering users, as individuals and as members of our society, by making possible the creation of a market place for a new class of distributed applications over wireless ad hoc networks. These wireless applications address the human need for organic and effective integration with the surrounding physical and social environment. Because no single application or system can fulfill the aspirations of human-centered computing, we believe that the answer rests with an open and competitive market place. This project is an investigation into the fundamental question of what is needed to create such a market place.